# Technological challenges of CLIC

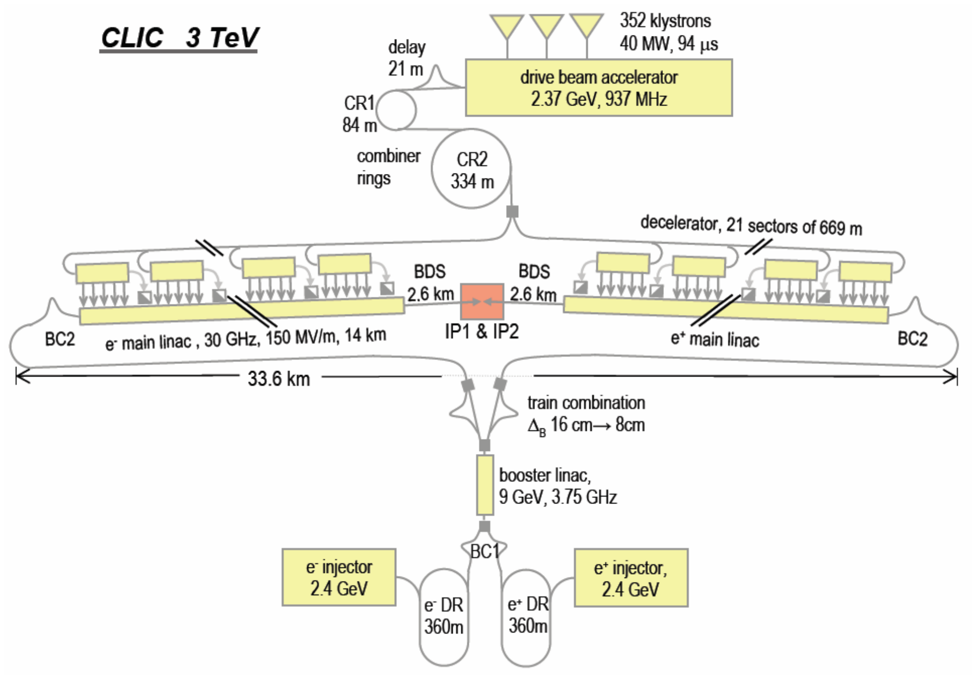
## 3. Materials for high gradients

Gonzalo Arnau Izquierdo – CERN

- Introduction
- Effect of high gradients on conventional materials
- Materials for high electric field
- Materials for high number of induced current pulses
- Production of bimetallic raw materials
- Machining to tight tolerances
- Conclusion and outlook

# Introduction

## Basic features of CLIC



*OVERALL LAYOUT OF CLIC*
*FOR A CENTER-OF-MASS ENERGY OF 3 TeV*

- High acceleration gradient (150 MV/m)

- "Compact" collider - overall length < 40 km
- Normal conducting accelerating structures
- High acceleration frequency (30 GHz)

- Two-Beam Acceleration Scheme

- Capable to reach high frequency
- Cost-effective & efficient (~ 10% overall)
- Simple tunnel, no active elements

- Central injector complex

- "Modular" design, can be built in stages

# Why such a high gradient ?

- Higher Gradient = shorter Accelerator
- Lower Cost
- Cultural threshold for maximum site length: 30-40 km
- Advantages for the beam dynamics

**Gradient as high as possible or economical:**
**150 MV/m for CLIC**

**Steffen Döbert, AB/RF, CERN Academic Training, 13 June 2006**

# Accelerating gradient ?

We need higher gradient per unit length (cost)

10 MV/m

15 – 30 MV/m: Routinely achieved (LIL)

50 MV/m: Super-conducting limit

100 MV/m

50 –150 MV/m:
Normal-conducting linear collider

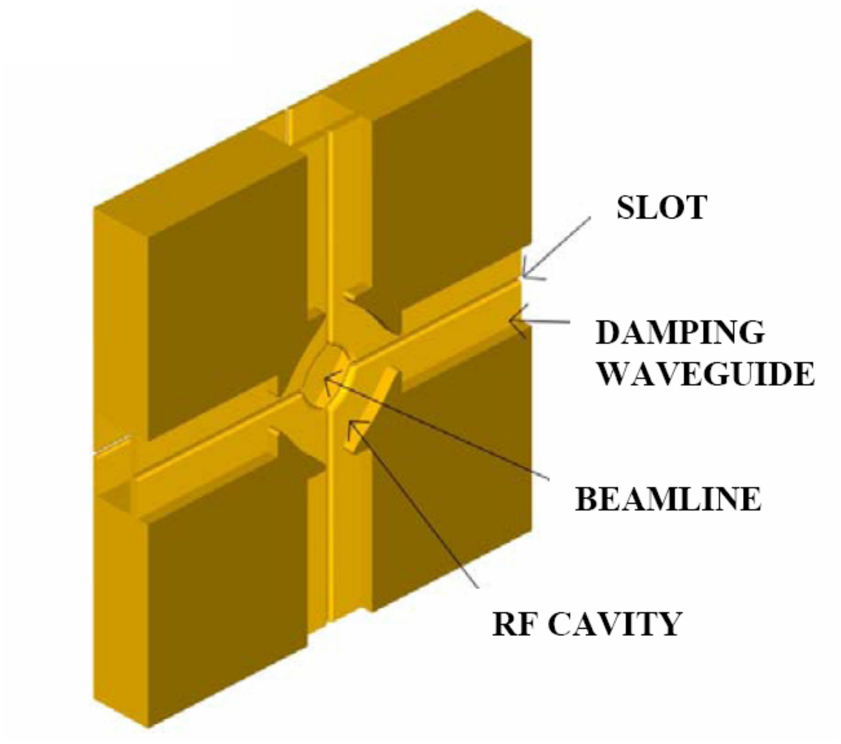
Future: Plasma/Laser/Wakefield acceleration

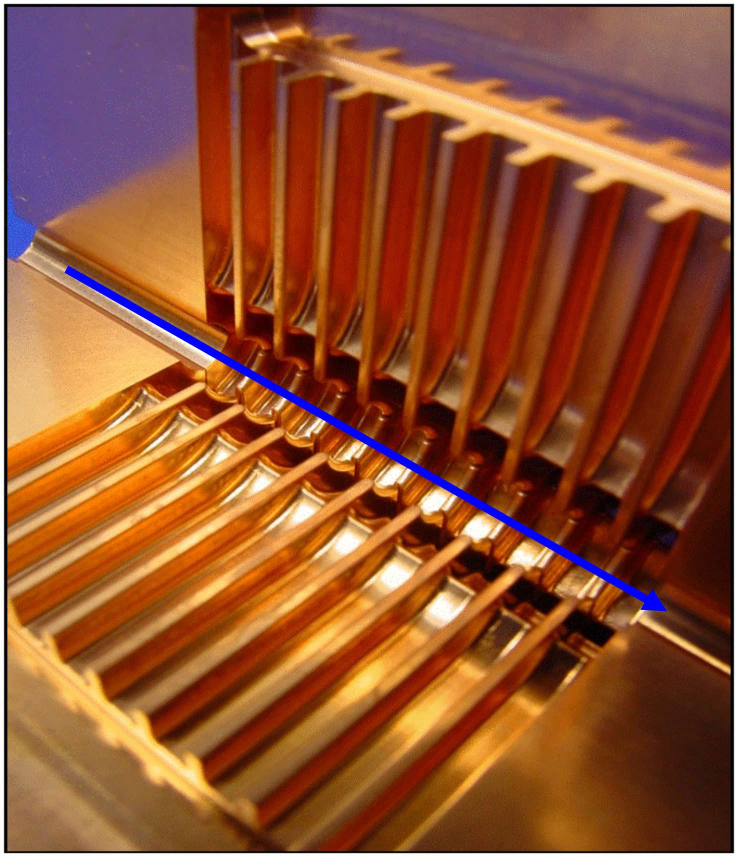
> 1 GV/m

**Steffen Döbert, AB/RF, CERN Academic Training, 13 June 2006**

# New Ideas from CLIC

## Accelerating structures **HDS** (Hybrid Dumped Structures)





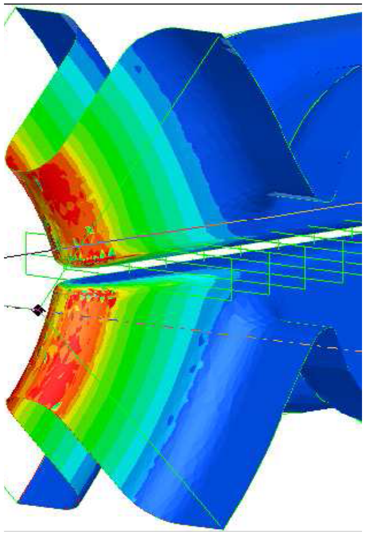
**30 GHz, 150 MV/m, 70 ns, < $10^{-6}$ trip probability**

# Effect of high gradient on conventional materials

# Materials of choice for **regions** of high accelerating gradient

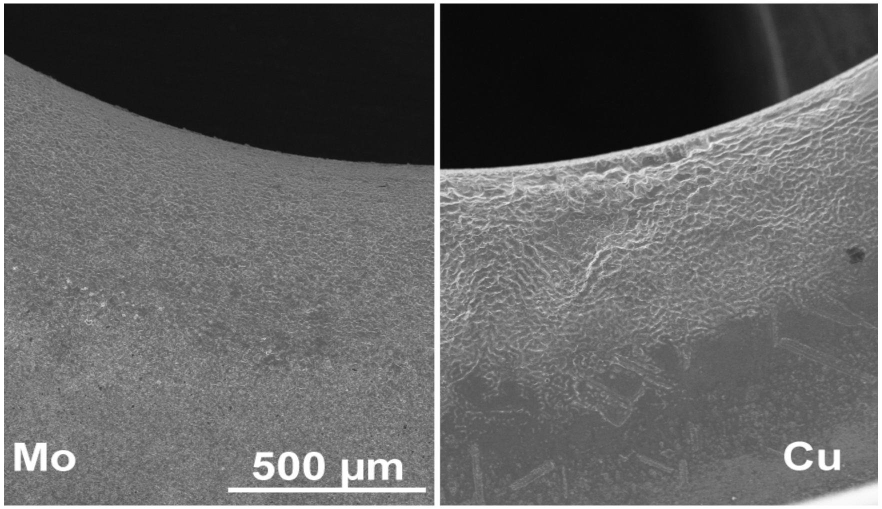
Iris: regions with **surface electric** field >300 MV/m

- ⇨ high field and breakdown events
- ⇨ geometry modification
- ⇨ use of Mo, or alternative refractory metal.



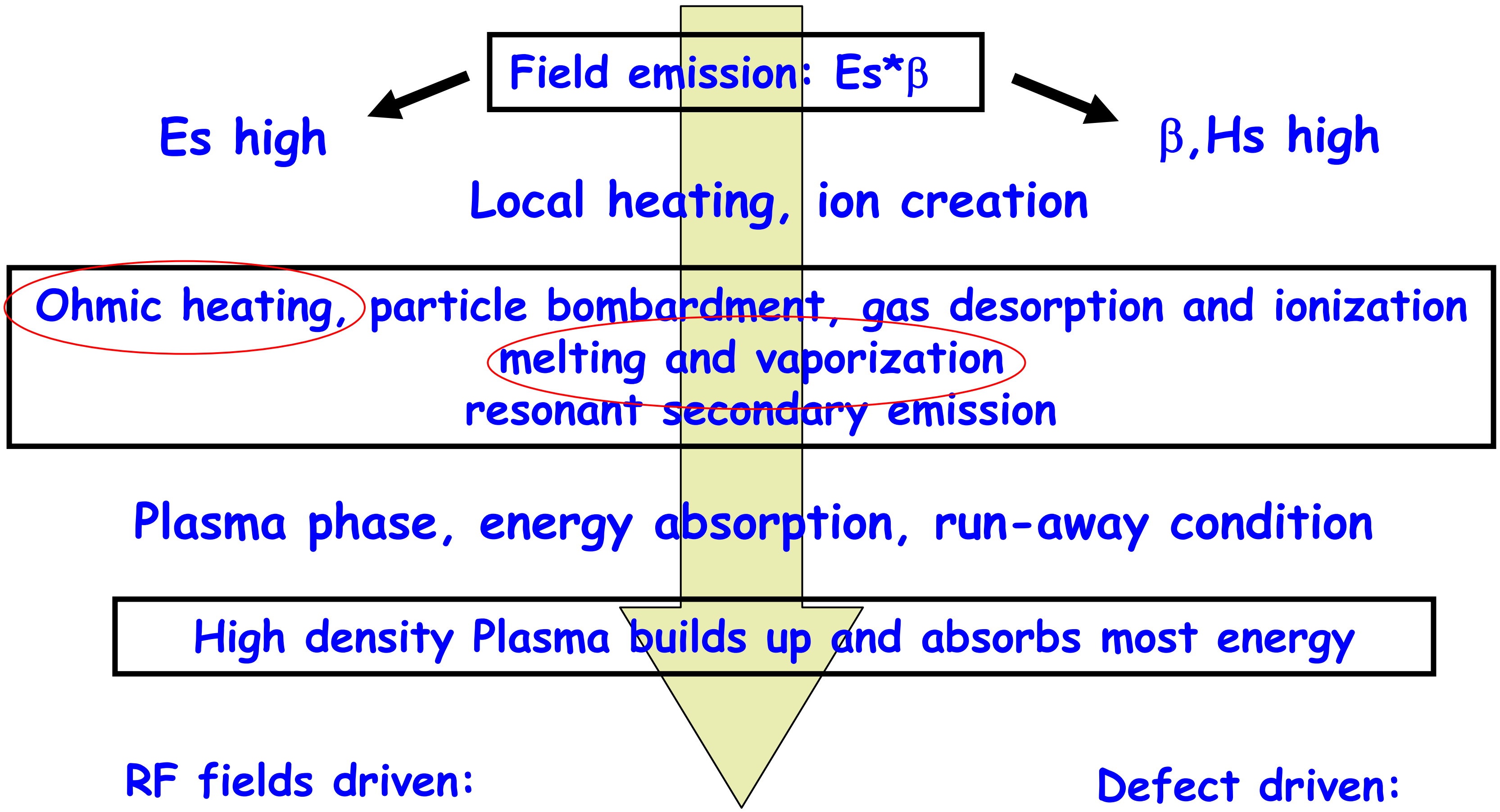
◄Surface electric field distribution in HDS cell.

▼Accelerating structures in Mo and Cu after RF tests at SLAC.



# What Happens in an RF breakdown

Breakdown Trigger



Field emission: Es*β

Es high

β,Hs high

Local heating, ion creation

Ohmic heating, particle bombardment, gas desorption and ionization
melting and vaporization
resonant secondary emission

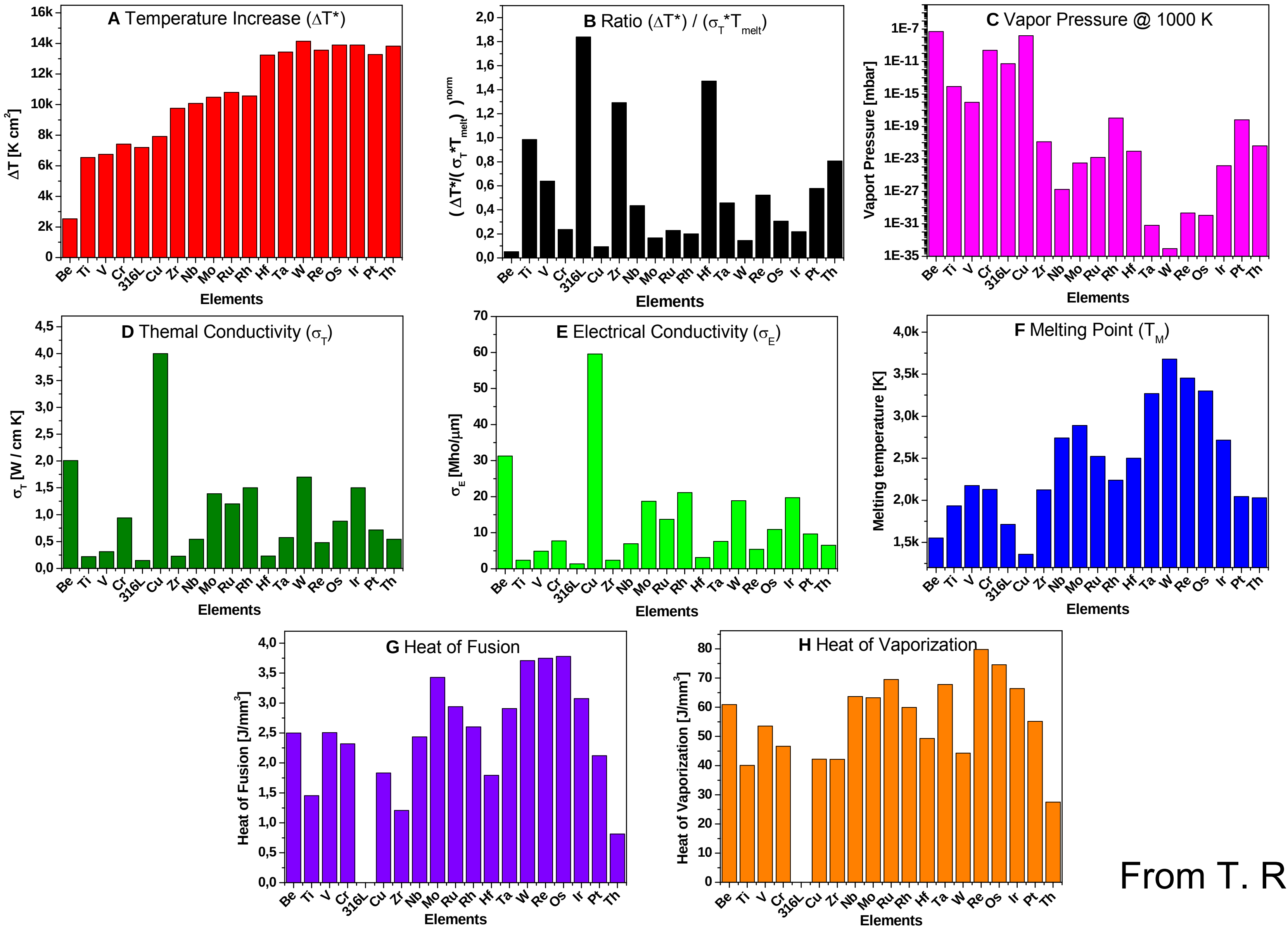
Plasma phase, energy absorption, run-away condition

High density Plasma builds up and absorbs most energy

RF fields driven:
high electrical surface fields

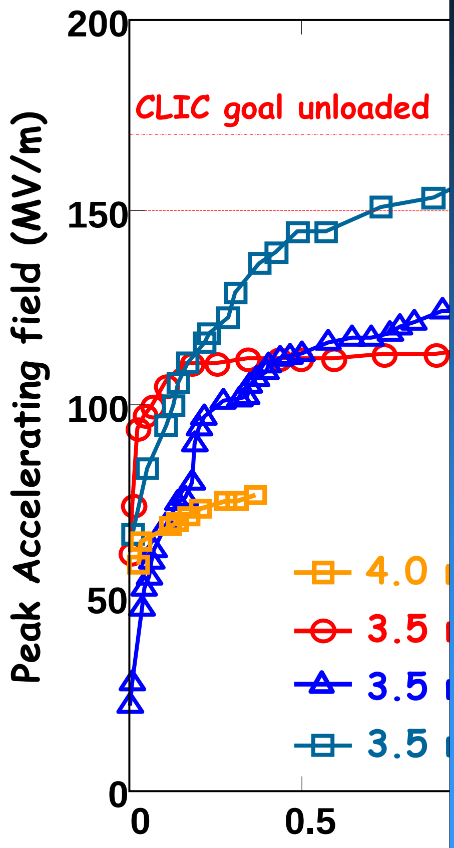
Defect driven:
Particles, voids, oxides

# Materials of choice for the regions of **high local pulsed currents**

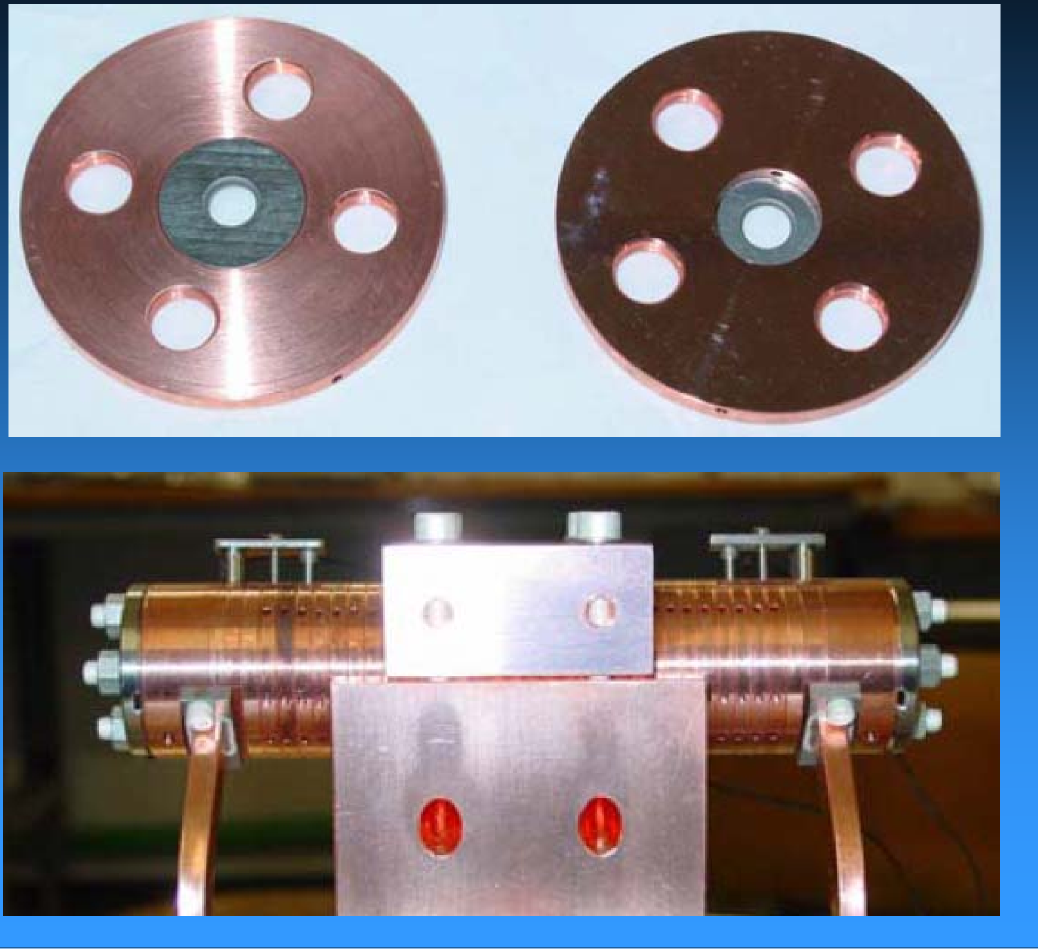


From T. Ramsvic

# Materials of choice for regions of **high accelerating gradient**



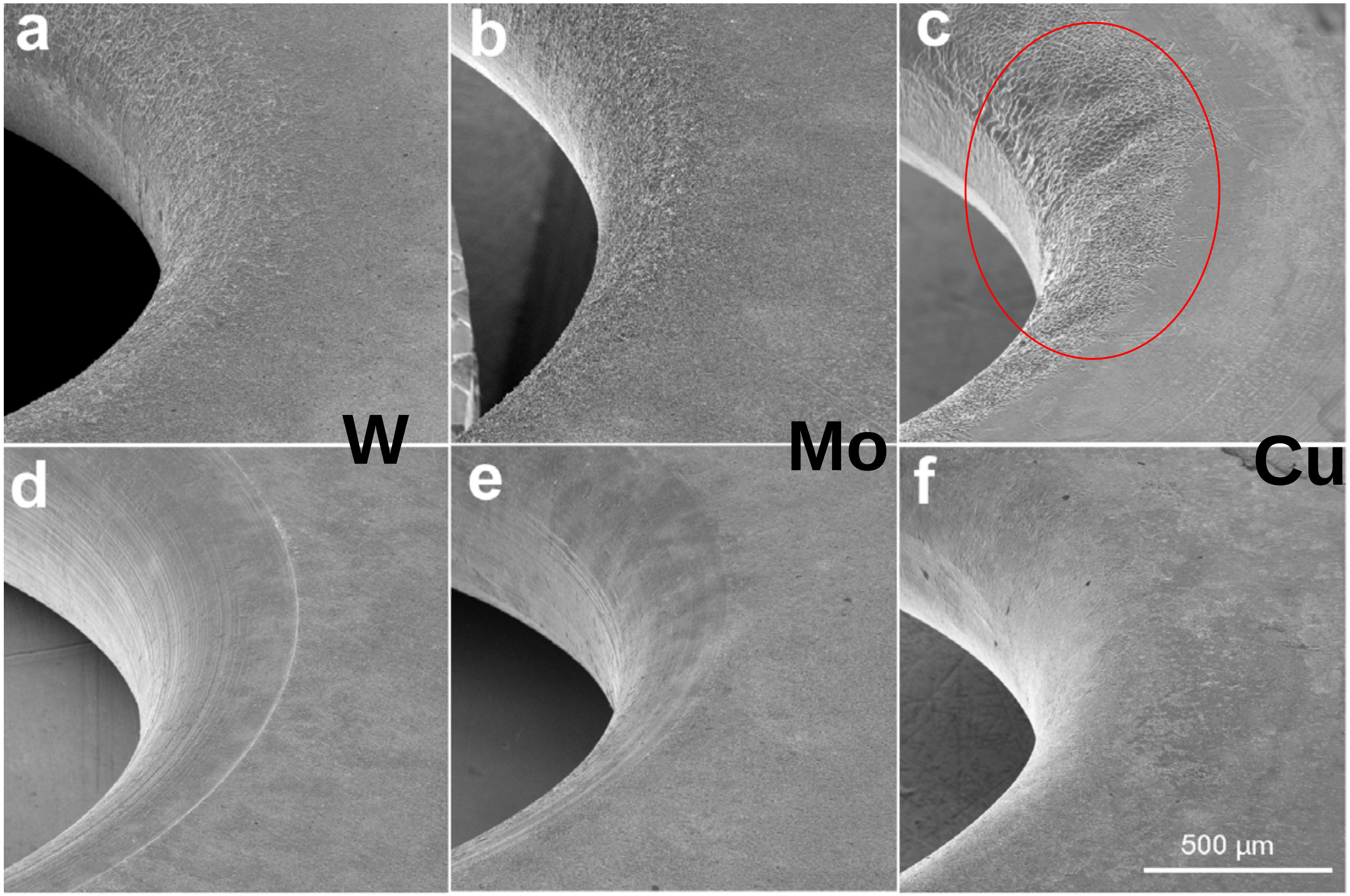
30-cell clamped tungsten-iris structure



A 30-cell structure with Mo irises and low $E_S/E_A$ largely exceeded the CLIC accelerating field requirements without any damage

190 MV/m accelerating gradient in first cell - tested with beam ! (but only 16 ns pulse length)

# Materials of choice for regions of **high accelerating gradient**



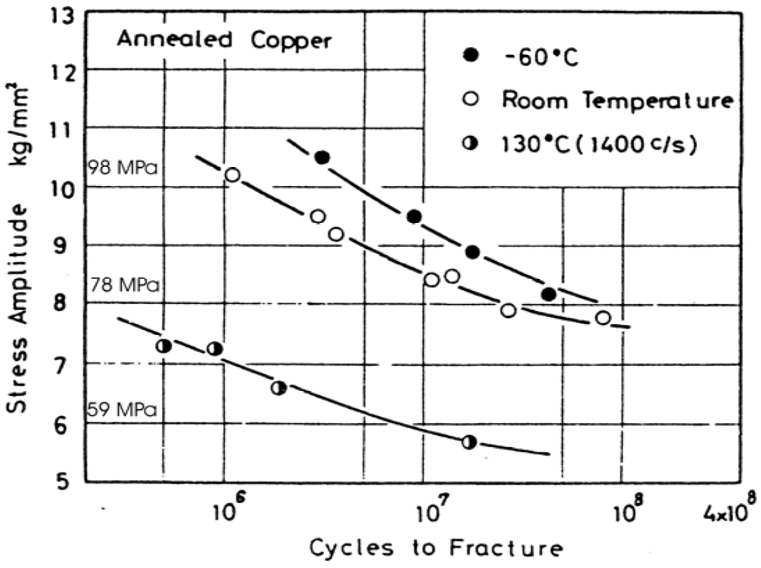
Damage on iris after runs of the 30-cell clamped structures of previous example tested in CTF2.
First (a, b and c) and generic irises (d, e and f) of W ,Mo and Cu structures respectively.

# Materials of choice for the **regions** of high local pulsed currents

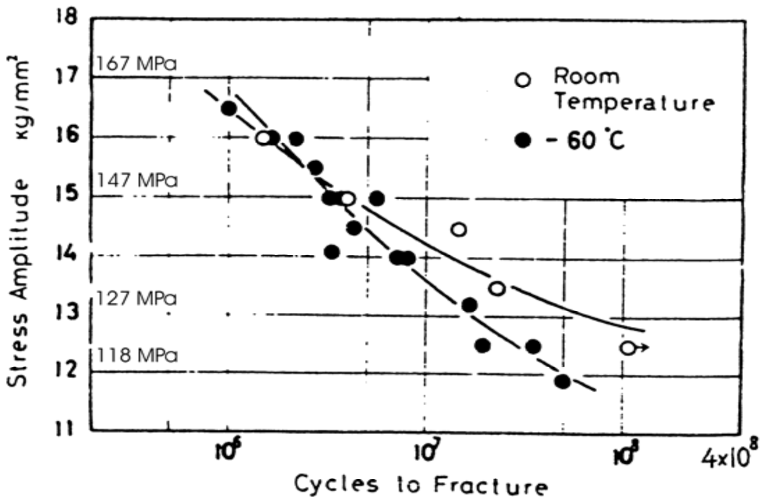
Periphery: regions with pulses of **magnetic field inducing surface currents**

- ⇨ ΔT= 56 K, $10^{11}$ cycles
- ⇨ pulsating compressive stress 0 to 155 MPa
- ⇨ fatigue surface damage

- ⇨ use of CuZr, or improved mechanical strength high conductivity alloy.



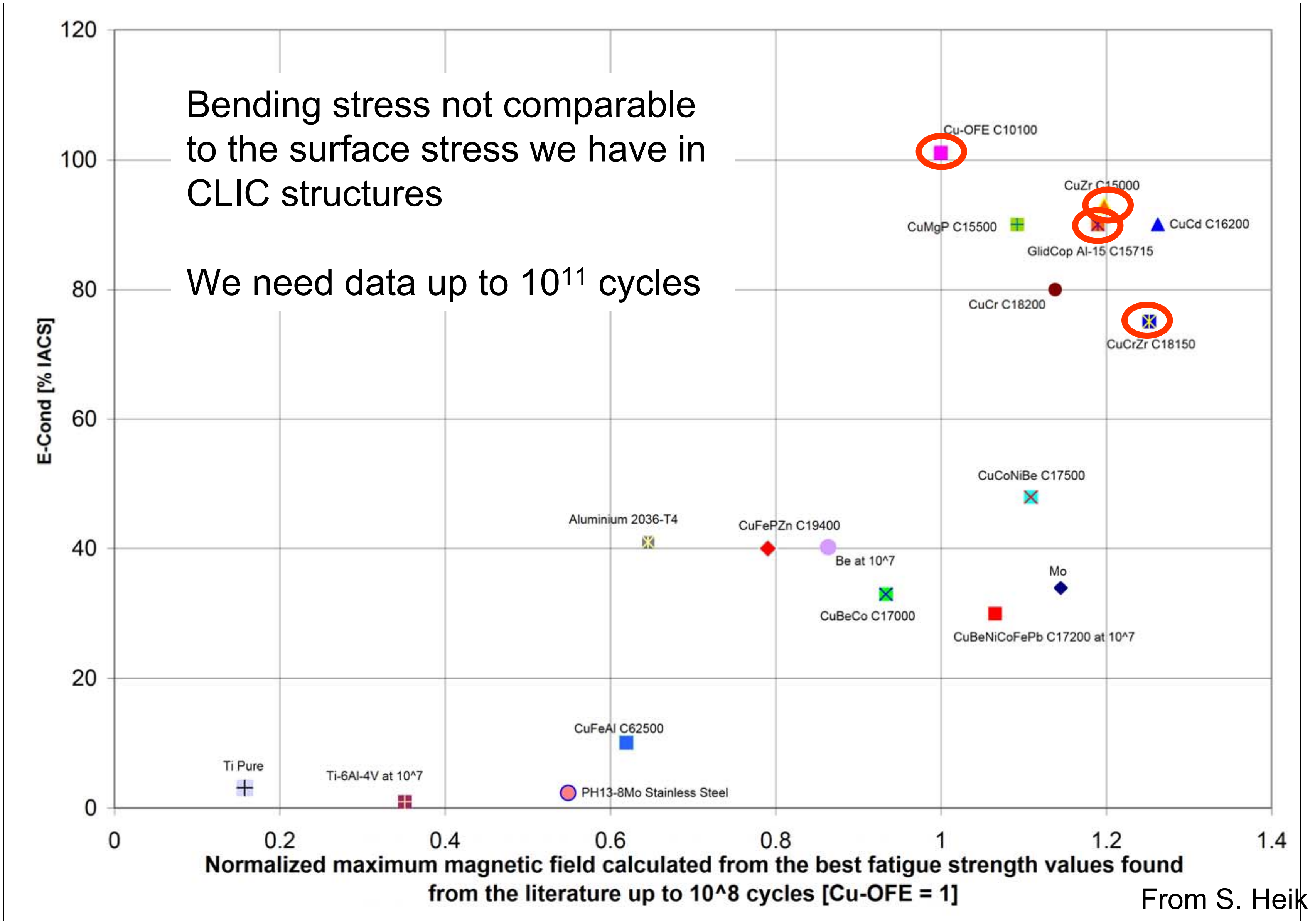
(a) Annealed copper



(b) Cold-worked copper

**Figure.** S-N curves or Wöhler curves describing the fatigue behavior of pure copper, Annealed and Cold Worked.

# Materials of choice for the regions of **high local pulsed currents**

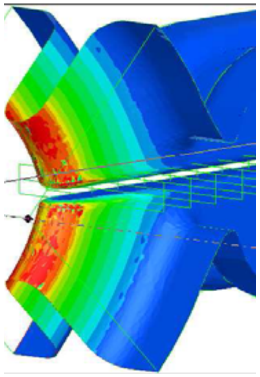


Bending stress not comparable to the surface stress we have in CLIC structures

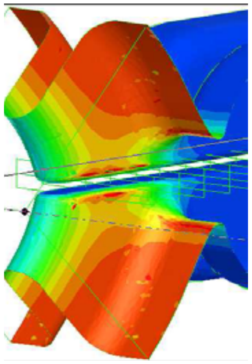
We need data up to $10^{11}$ cycles

From S. Heikkinen

# How to make a bi-metal HDS structure with Mo iris and CuZr body?

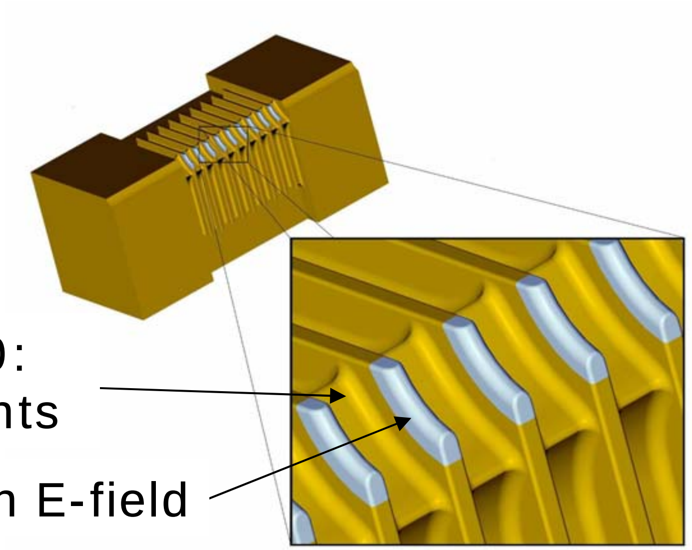


⇨use of **Mo**, or alternative refractory metal.



⇨ use of **CuZr**, or improved mechanical strength high conductivity alloy.

⇨Use bi-metallic



CuZr C15000:
Pulsed currents

Mo: high E-field

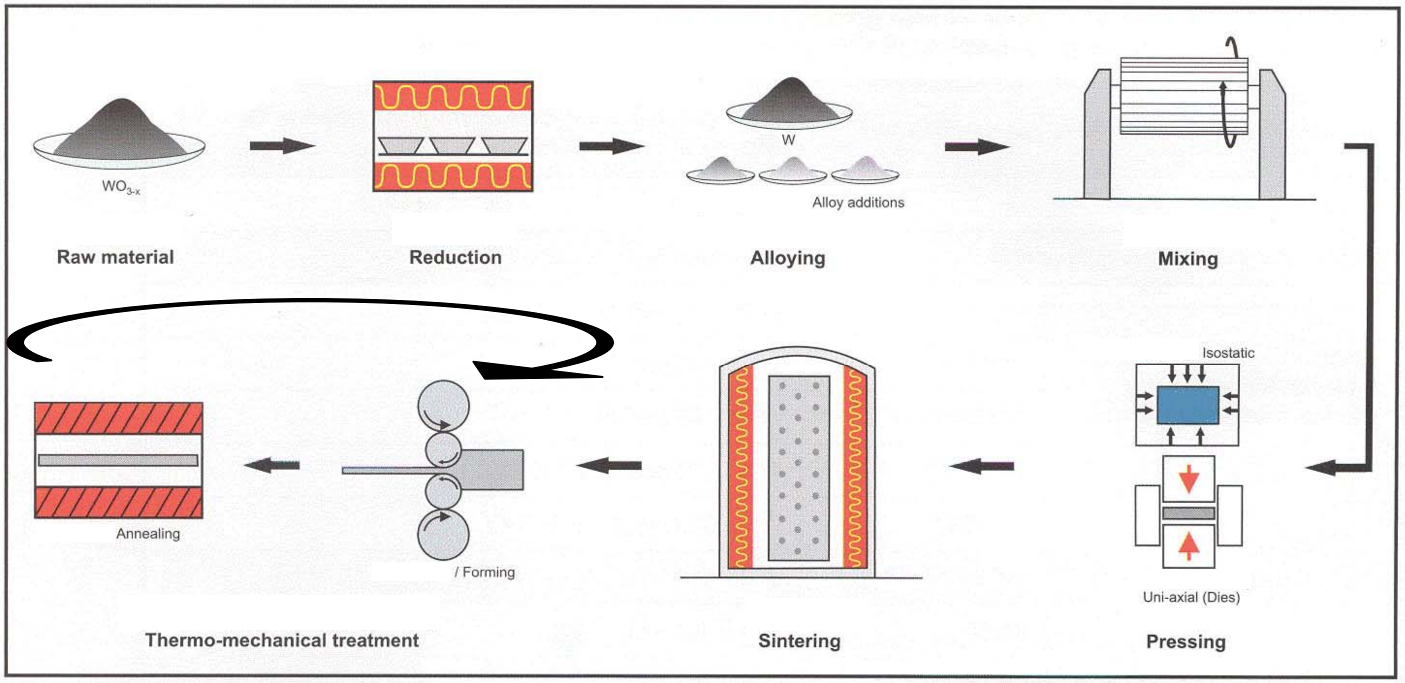
Aims:
- Join CuZr and Mo
- Machine to +/- 1µm accuracy, 0.05µm Ra close to the beam region

# Materials for high electric field (Mo, W)

- Processing
- Recrystallization risk
- Machining
- Ongoing R&D
  - DC spark test system
  - Mono-metal prototypes for RF testing in CTF3

# Mo/W processing and properties

- Semi-finished products of refractory metals are almost exclusively originated from powder metallurgy (PM).
    - Purities >99.97 %wt are common.
    - (Electron beam melting can be used for further purification)
- Powder is pressed into rods or plates
- Sintering in $H_2$ flow at 2000 – 2200 ºC Mo / 2500 ºC W
- (Hot) forming
- Intermediate annealing for recovery and recrystalization
- Thin wire and foils can be cold drawn and rolled



Schematic flow of the production of semi-finished products

*Fig. 22: Microstructure after sintering (top), after forming (middle), after recrystallization (bottom) a hundred times enlarged*

# Mo/W recrystallization risk

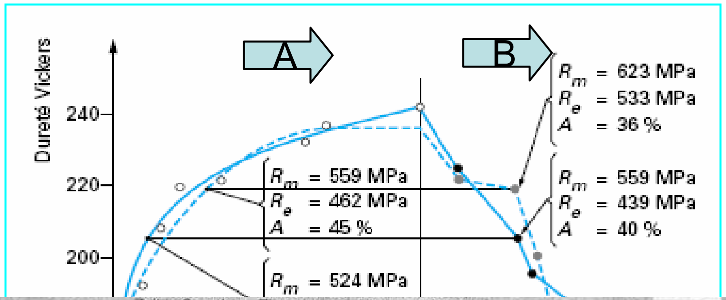
**Risk of grain boundary fragility by stays at high-temperature**

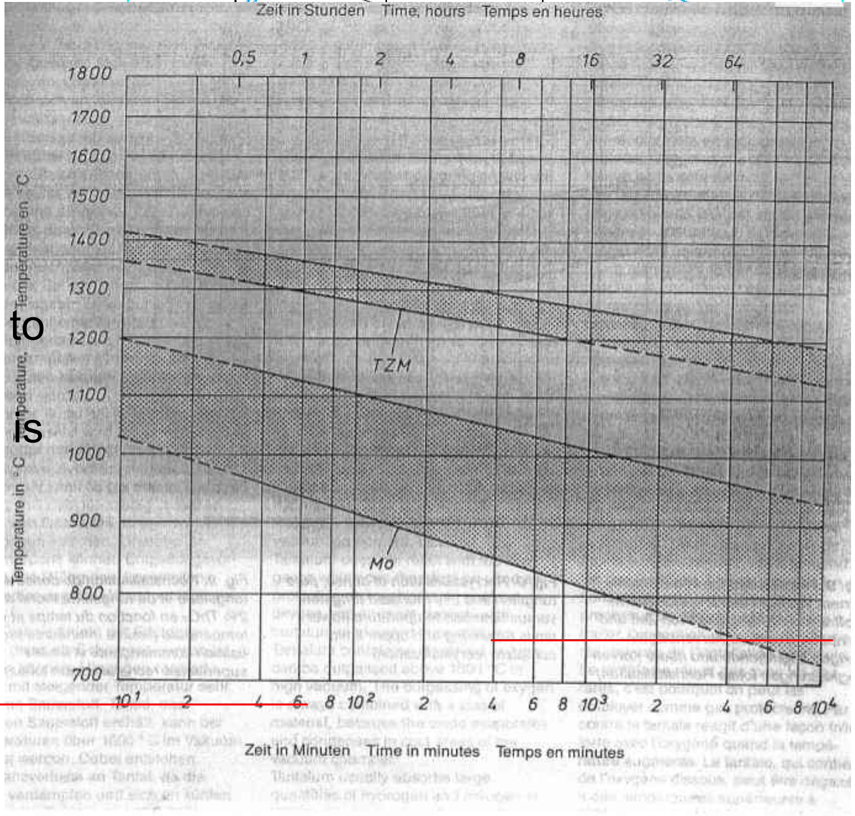
Ductility, fracture toughness, hardness and strength decrease with increasing levels of recrystallization.
!! Possibly misleading: in most non-refractory metals recrystallization increases ductility and fracture toughness with respect to the cold-worked state.

Recrystalization temperature depends on
- time at temperature
- previous mechanical working
- addition of dispersoids →grades alternative to pure Mo and W

The minimum recrystalization temperature for Mo is 900ºC for W is 1100ºC

Grain boundary fragility can only be reversed by mechanical work. A

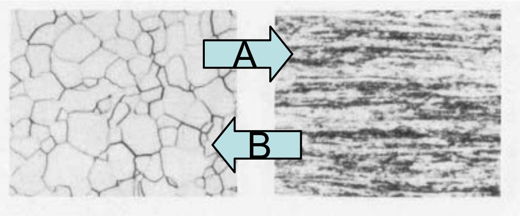




Rekristallisation von dichtem, Molybdän und TZM in Abhän- von Zeit und Temperatur (untere begrenzungen: beginnende, Kurvenbegrenzungen: totale allisation)

*Fig. 8: Recrystallization of dense, pure molybdenum and TZM versus time and temperature (lower limits: the beginning and upper limits: the completion of recrystallization)*

*Fig. 8: Recristallisation de dense et pur molybdène et TZM en fonction du temps et de la température (limites inférieures: recristallisation commençante et limites supérieures: recristallisation totale)*



# Mo/W machining

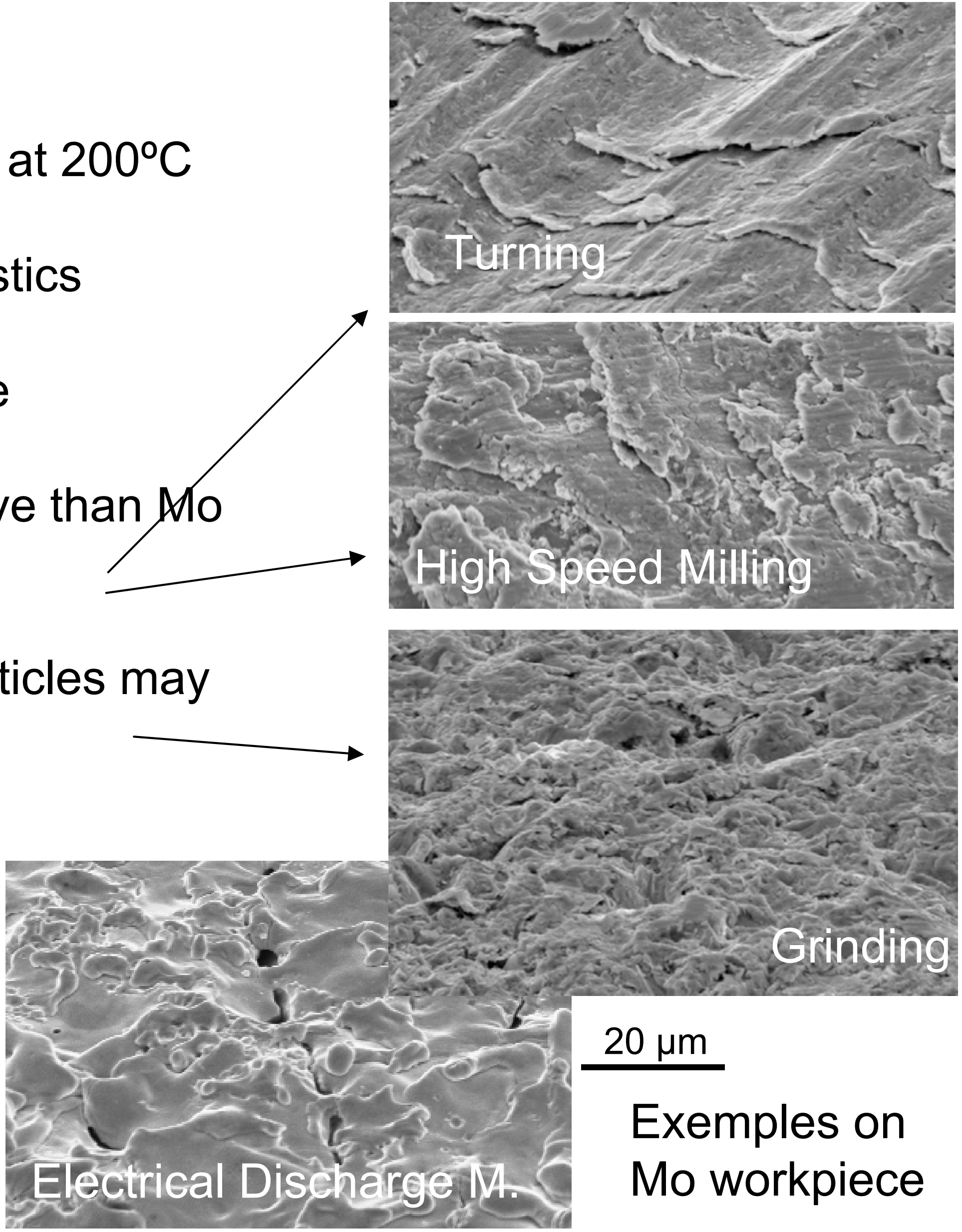
Conventional machining properties:

- W is difficult to machine, preheating at 200ºC is recommended
- Mo has better machining characteristics "similar to cast iron"
- Carbide tools and rigid mounting are recommended
- Tool wear is high, W is more abrasive than Mo
- Surface has tendency to chip

Grinding with silicon carbide wheels, particles may be embedded.

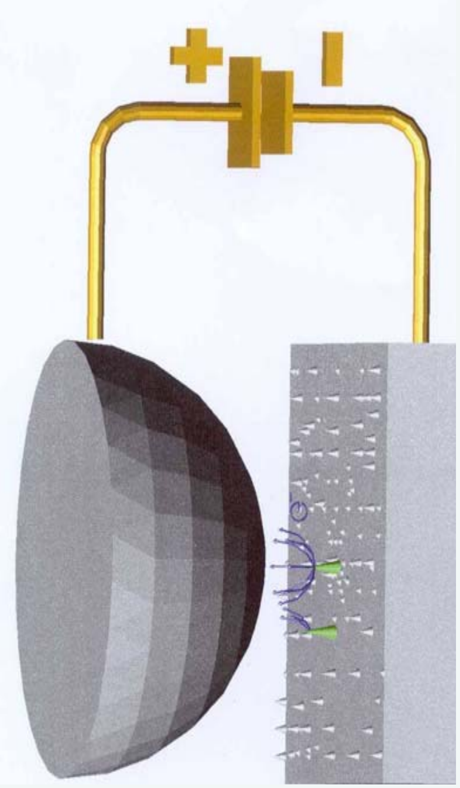
Electrical Discharge Machining

- Electrode wear is high
- Surface presents Recast layer with microcracks



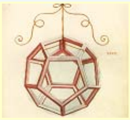
Exemples on Mo workpiece

# DC Spark Test System for CLIC



*Trond Ramsvik*
*TS / MME*
*27 January 2006*

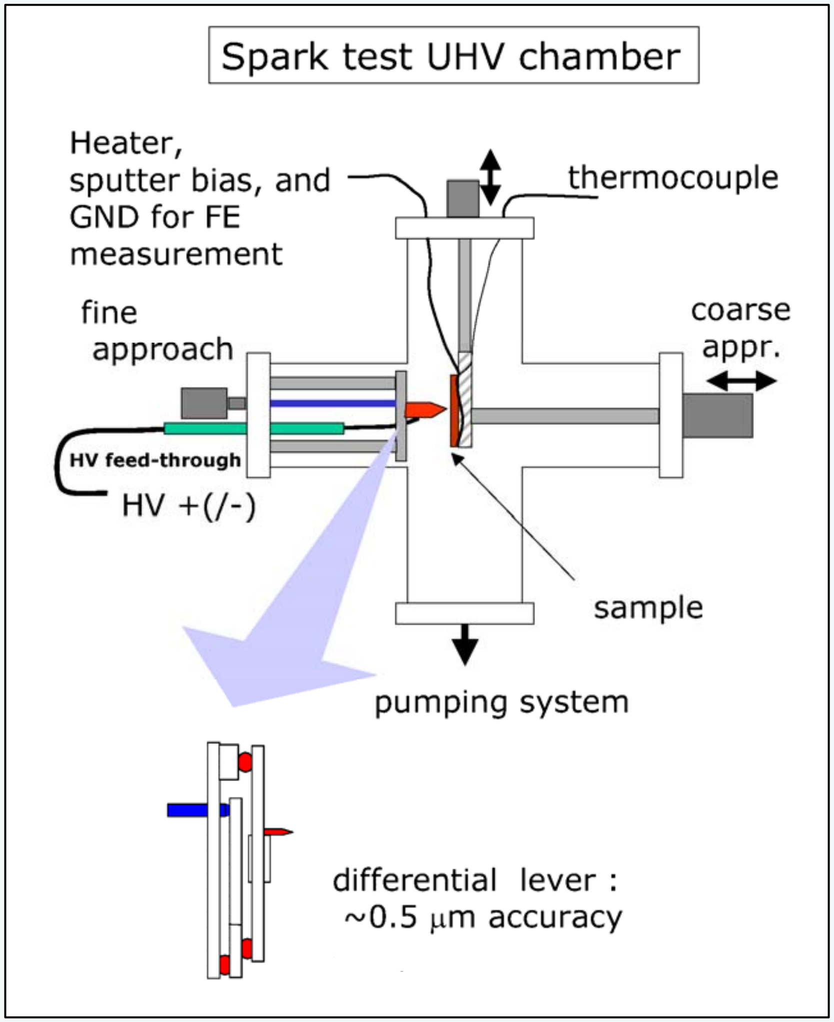
# Introduction: Why DC spark experiments?

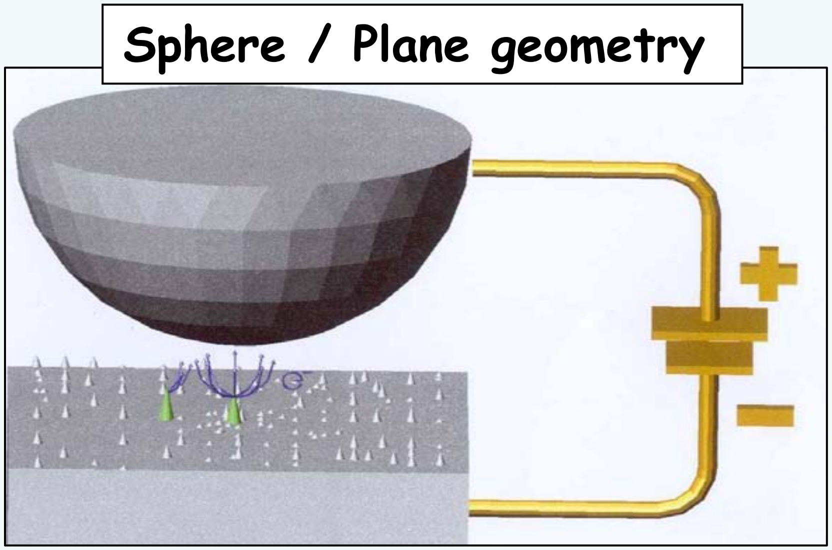


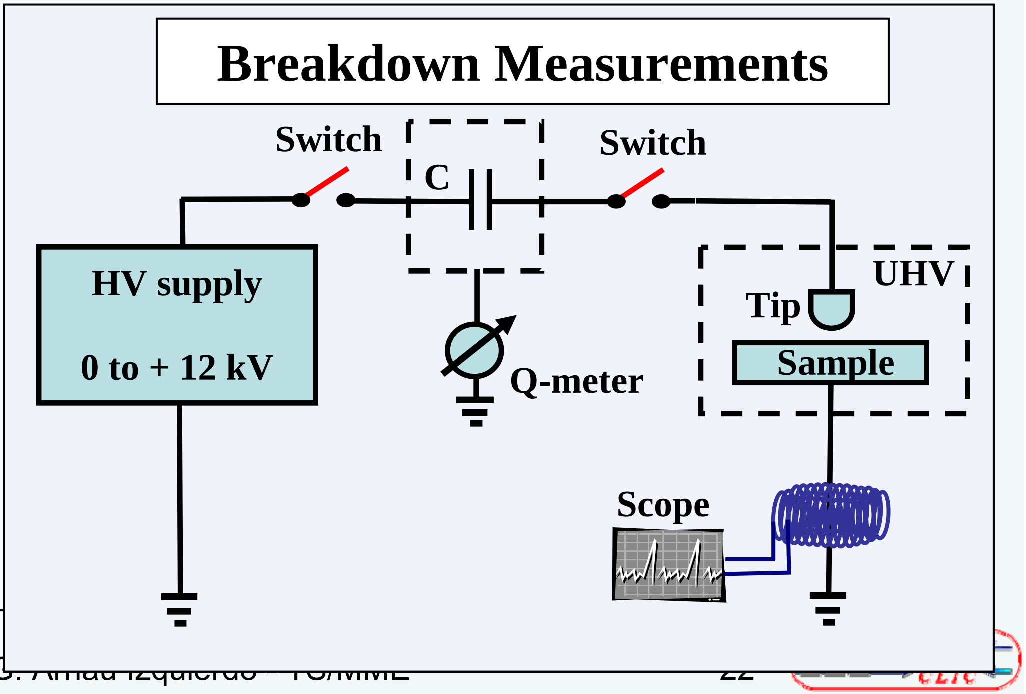
***With a simple DC spark-test system, the properties of various materials can be studied at high electric fields in an easy and controlled way.***

**Goal: To find materials that withstand the highest field without breakdown or have low level of deterioration even when breakdown events occur.**

# Experimental Setup

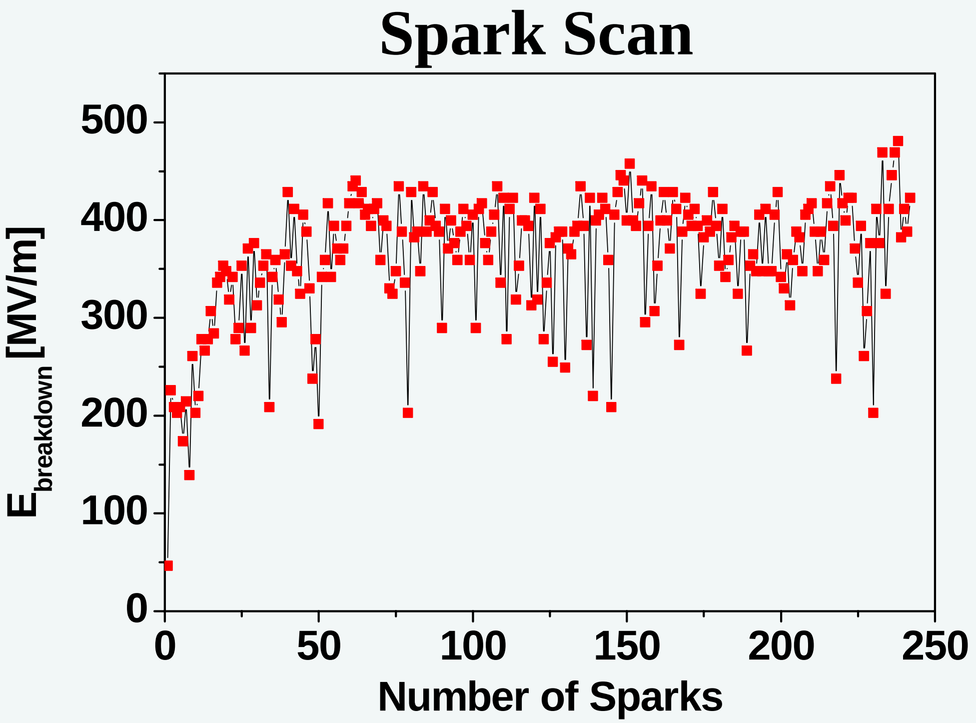


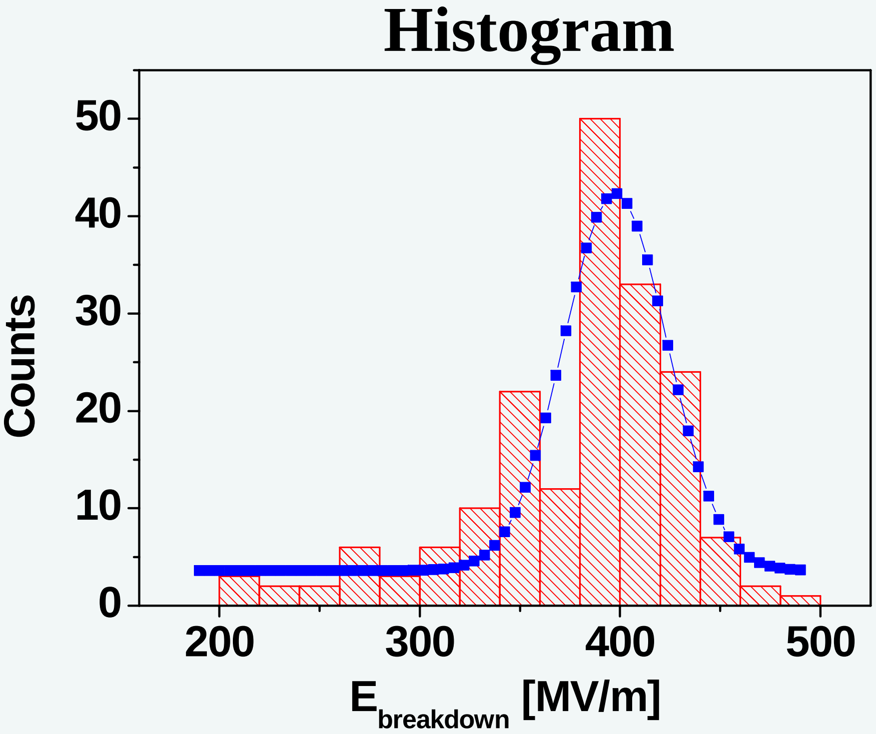




# Automatic Spark Conditioning

## Molybdenum (Mo) - Tip and Sample

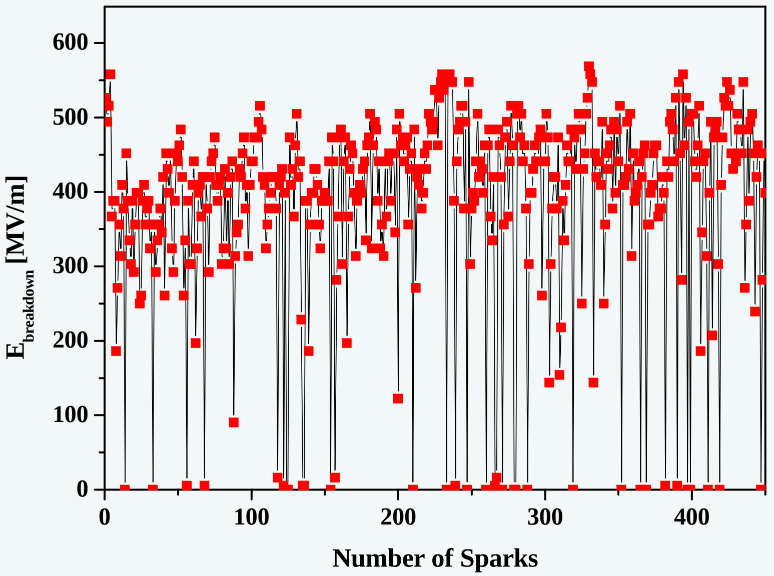


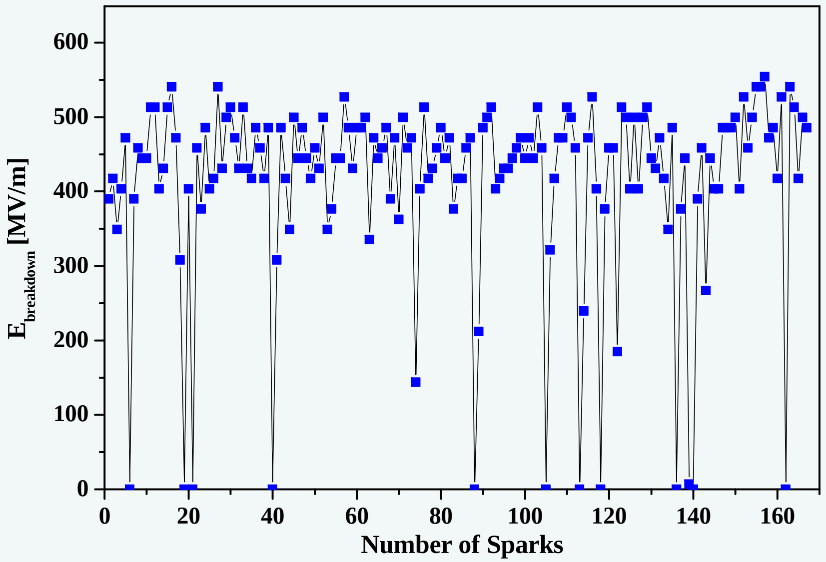


$$E^{sat}_{breakdown} \cong (398 \pm 4)\ MV/m\ at \sim 4 \times 10^{-8}\ mbar$$

# Mo - heated with e-beam

*not re-crystallized*
*~ 4 hours in air between heating and mounting in spark system*





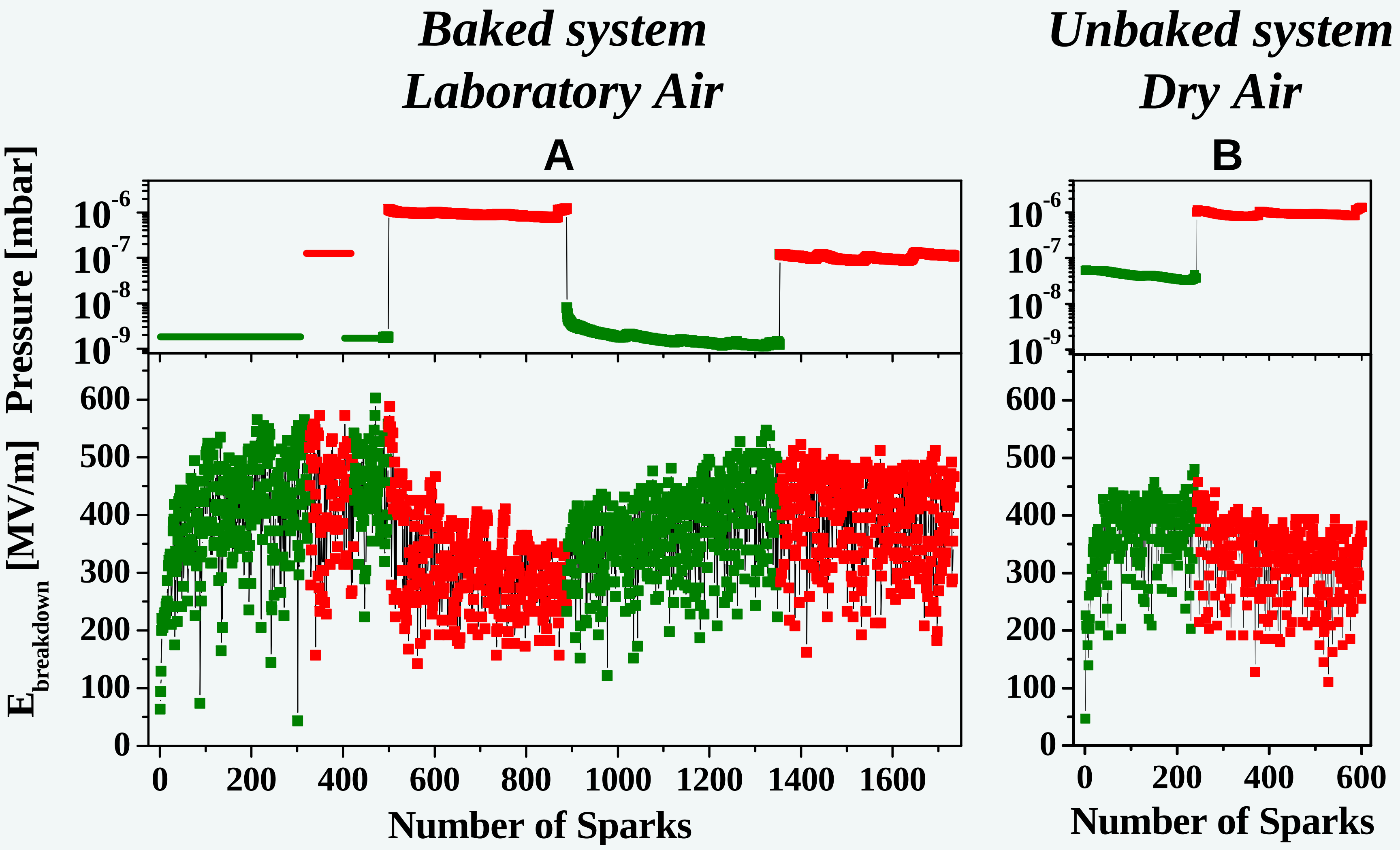
*Initial Breakdown Field:*
*~ 350 MV/m*

*Conditioning with "normal" speed to ~450 MV/m*

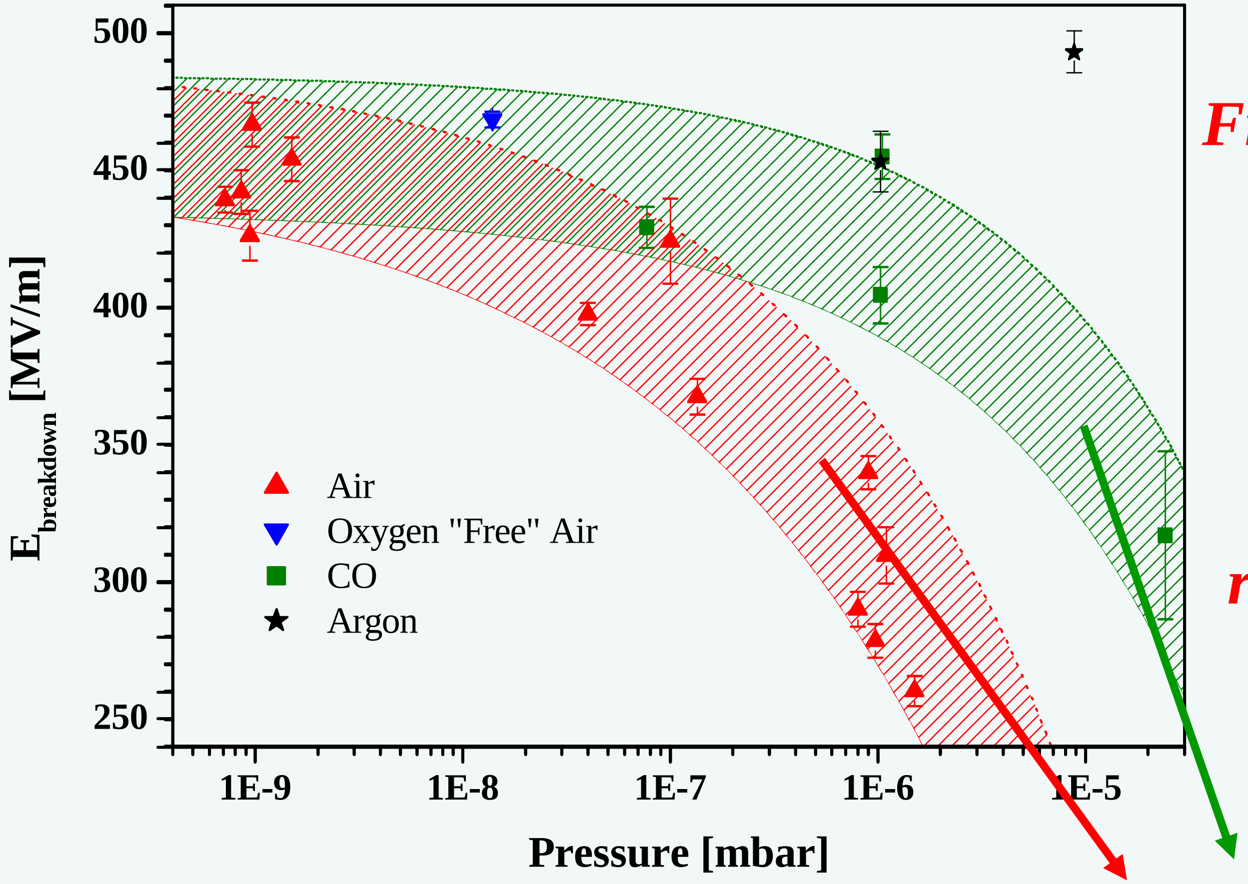
*Conditioning almost immediately to ~450 MV/m*

**Ebeam heated in University of Geneva 25.10.2005,**

# *Gas Experiments - Air/Mo*



# Gas Experiments – (Air-CO)/Mo



From ~$10^{-9}$ to ~ $10^{-6}$ mbar of air

⬇

The saturated breakdown field is reduced by ~<u>140 MV/m</u>

$$E_{breakdown}^{0\ mbar,\ CO} = (465 \pm 30)\ MV/m$$

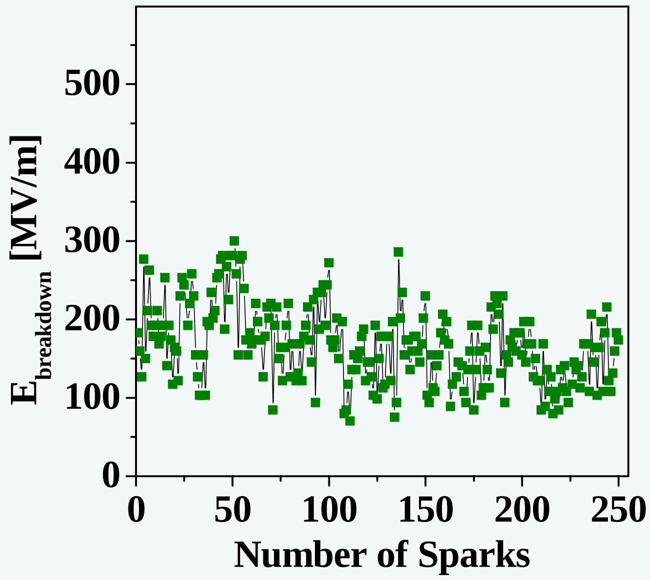
$$k_{CO} = (12425 \pm 1008)\ MV/m\ (mbar)^{-1}$$

$$n_{CO} = (0.42 \pm 0.02)$$

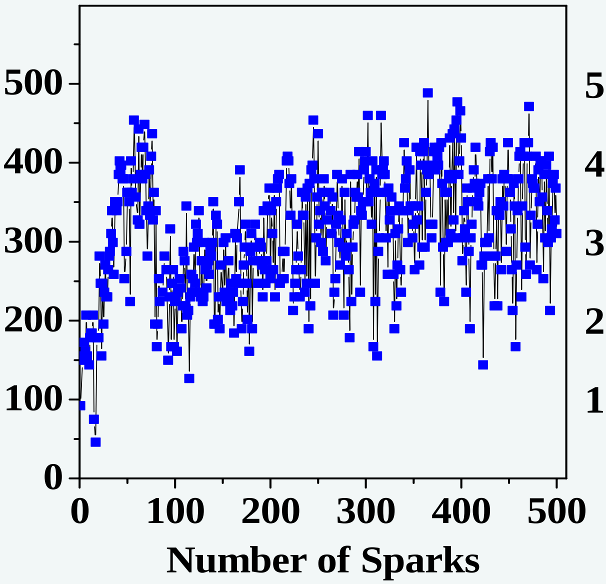
$$\boxed{E_{breakdown} = E_{breakdown}^{0\ mbar} - k \cdot \{P\}^{n}}$$

# Comparison Cu – W – Mo

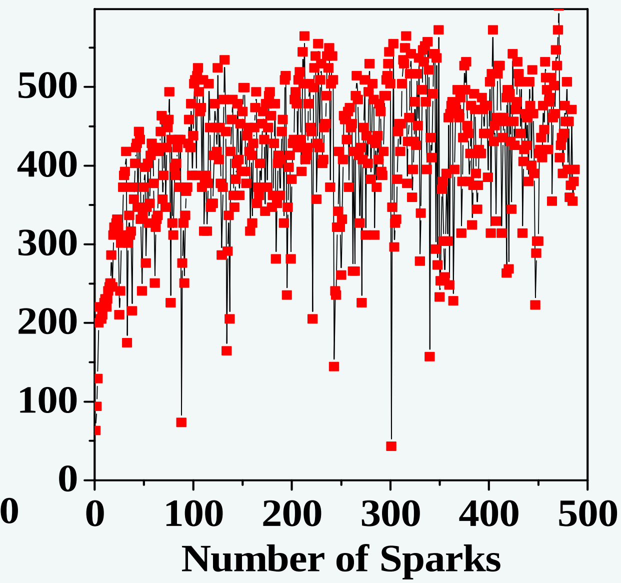
**Copper**



**Tungsten**



**Molybdenum**

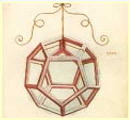


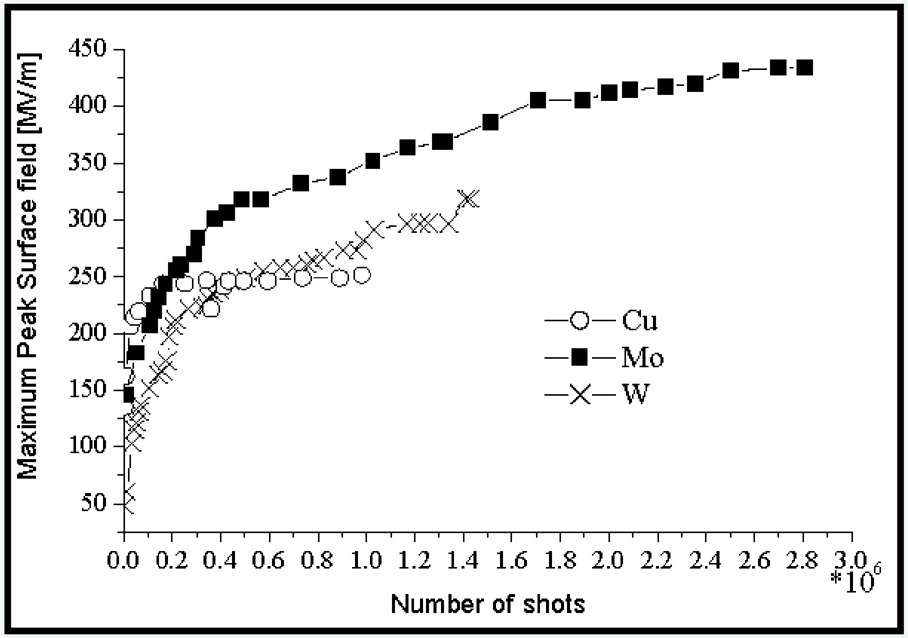
**Cu:** $E_{\mathrm{breakdown}}^{\mathrm{sat}} \cong (159 \pm 3)\ \mathrm{MV/m\ at} \sim 7 \times 10^{-10}\ \mathrm{mbar}$

**W:** $E_{\mathrm{breakdown}}^{\mathrm{sat}} \cong (349 \pm 6)\ \mathrm{MV/m\ at} \sim 2 \times 10^{-08}\ \mathrm{mbar}$

**Mo:** $E_{\mathrm{breakdown}}^{\mathrm{sat}} \cong (431 \pm 7)\ \mathrm{MV/m\ at} \sim 2 \times 10^{-09}\ \mathrm{mbar}$

# Comparisons - 30 GHz measurements

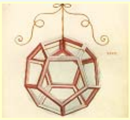




| | $E^{sat}_{breakd}$ (DC) [MV/m] | Max. surface field in RF [MV/m] |
|---|---|---|
| **Cu** | 160 | 241 |
| **W** | 349 | 329 |
| **Mo** | 430 | 420 |

- ***DC and RF breakdown measurements give similar breakdown fields for Mo and W***
- ***Superior behavior of both Mo and W with respect to Cu.***

# Future Projects



## Continue the study of various materials

- TiVAl
  - higher tensile strength than pure Titanium
  - → maintain low beta, and avoid severe erosion ?
- Glidcop, CuZr
  - higher resistance to fatigue than pure Copper
- Mo-Re alloys
  - study the effect of increased tensile strength, while maintaining similar properties as Mo
- Chromium
- Sputter Cleaned Molybdenum
  - study the effect of molybdenum oxide on the surface
- (others)

## Regulate the energy over the gap junction

## In-situ annealing and sputtering of samples

# Prototype RF testing in CTF3

Coming soon: prototype structures for testing at high power RF in CTF3

Manufactured in:
stainless steel,
Ti, Al, CuOFE, Mo

To be manufactured in
bi-metal Mo-CuZr

Target accuracy of
+/- 5 µm

# Materials for high number of induced current pulses (Cu, CuZr, GlidCop)

- Cu, CuZr Processing
- Strain hardening
- Precipitation hardening (CuZr)
- Dispersion hardening (GlidCop)
- Ongoing R&D
  - Laser pulse and ultrasonic fatigue tests

# Production of Coppers and High-copper alloys

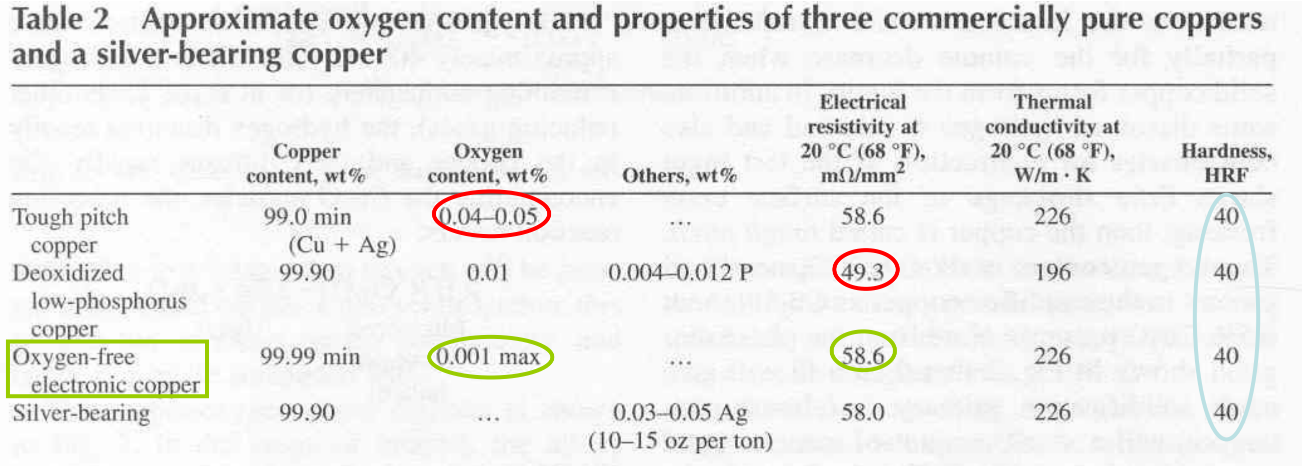
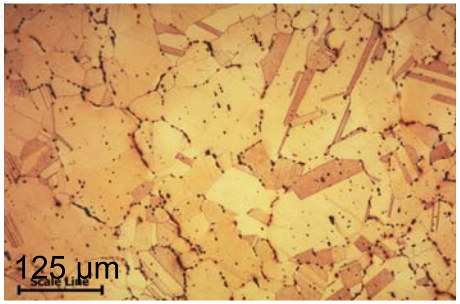


**Table 2 Approximate oxygen content and properties of three commercially pure coppers and a silver-bearing copper**

| | Copper content, wt% | Oxygen content, wt% | Others, wt% | Electrical resistivity at 20 °C (68 °F), mΩ/mm² | Thermal conductivity at 20 °C (68 °F), W/m · K | Hardness, HRF |
|---|---|---|---|---|---|---|
| Tough pitch copper | 99.0 min (Cu + Ag) | 0.04–0.05 | … | 58.6 | 226 | 40 |
| Deoxidized low-phosphorus copper | 99.90 | 0.01 | 0.004–0.012 P | 49.3 | 196 | 40 |
| Oxygen-free electronic copper | 99.99 min | 0.001 max | … | 58.6 | 226 | 40 |
| Silver-bearing | 99.90 | … | 0.03–0.05 Ag (10–15 oz per ton) | 58.0 | 226 | 40 |

Vapor pockets in an ETP copper



Problem of oxygen bearing coppers (tough pitch):

- O is in the form of $Cu_2O$ inclusions
- At T> 400 ºC in H containing or reducing atmosphere, H diffuses and reacts with the oxide inclusions forming steam
- Inclusions leave behind a porous structure with reduced strength

→ Not suitable if heating in reducing atm. during production, assembly or service

→ Use oxygen free or deoxidized coppers

Deoxidized coppers contain phosphorous

- P content lowers conductivity considerably

→ Use oxygen free coppers

All pure coppers have equivalent mechanical properties at RT

CuZr and GlidCop are based on oxygen free copper

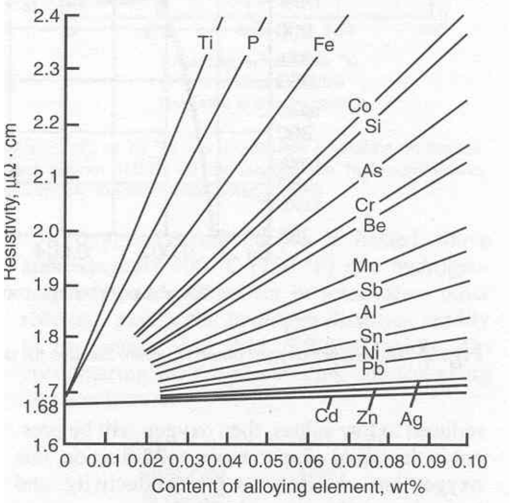
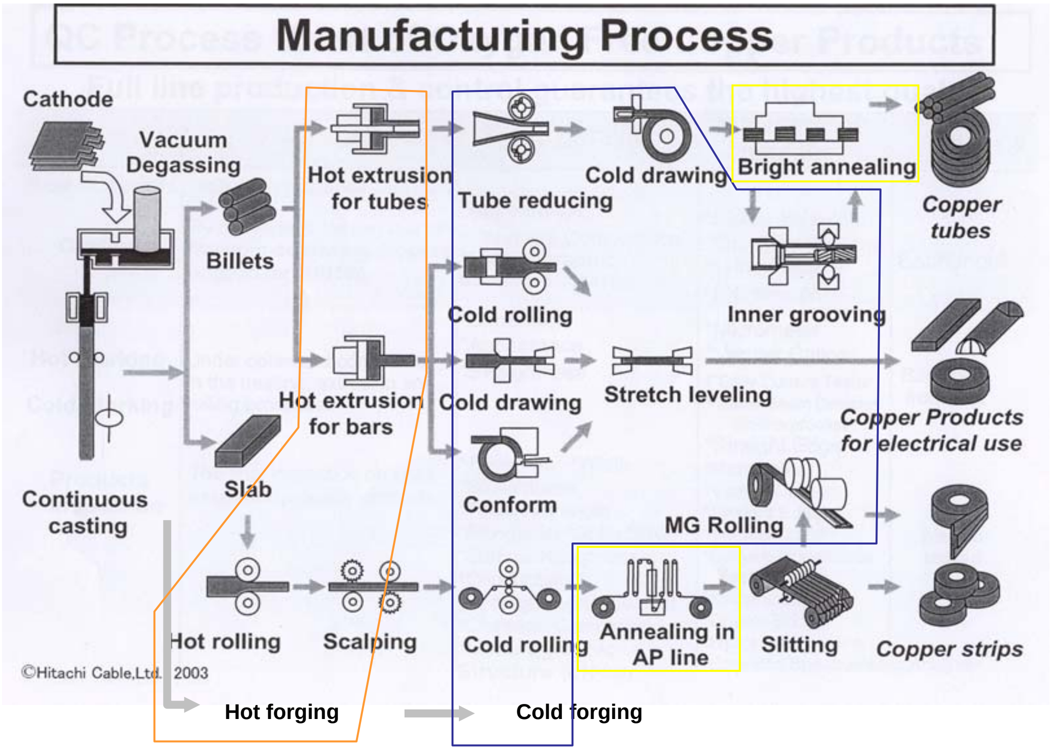


**Fig. 1** Effects of alloying elements on electrical resistivity of copper. Note: an increase in resistivity, ρ, is equivalent to a decrease in electrical conductivity, σ,

# Production of wrought forms



Hot forming
- Above recrystallization temperature (750 -875 ºC)
- Dynamic recrystalization
- Homogenizes and compacts as-cast microstructure

Cold forming
- Below recrystallization temperature to RT
- Hardening effect (Cold-work)
- Microstructure of deformed grains

Annealing
- Made if product is needed soft or if further cold forming has to be facilitated.
- Softening effect
- Microstructure may recrystallize and, if excessive, grain coarsen.
- Cu-OFE 375-650 ºC
- CuZr 600-700 ºC

# Strain-hardening (by cold-work)

**Cold work** introduces lattice defects whose effect are

- Increasing strength and hardness
- Decreasing elongation
- Slightly decreasing electrical conductivity

Cold work hardens all metals

Is the only hardening possibility for very pure metals like Cu-OFE

**Annealing** is a thermal treatment that restores the lattice (annihilates the defects) and the mechanical and electrical properties

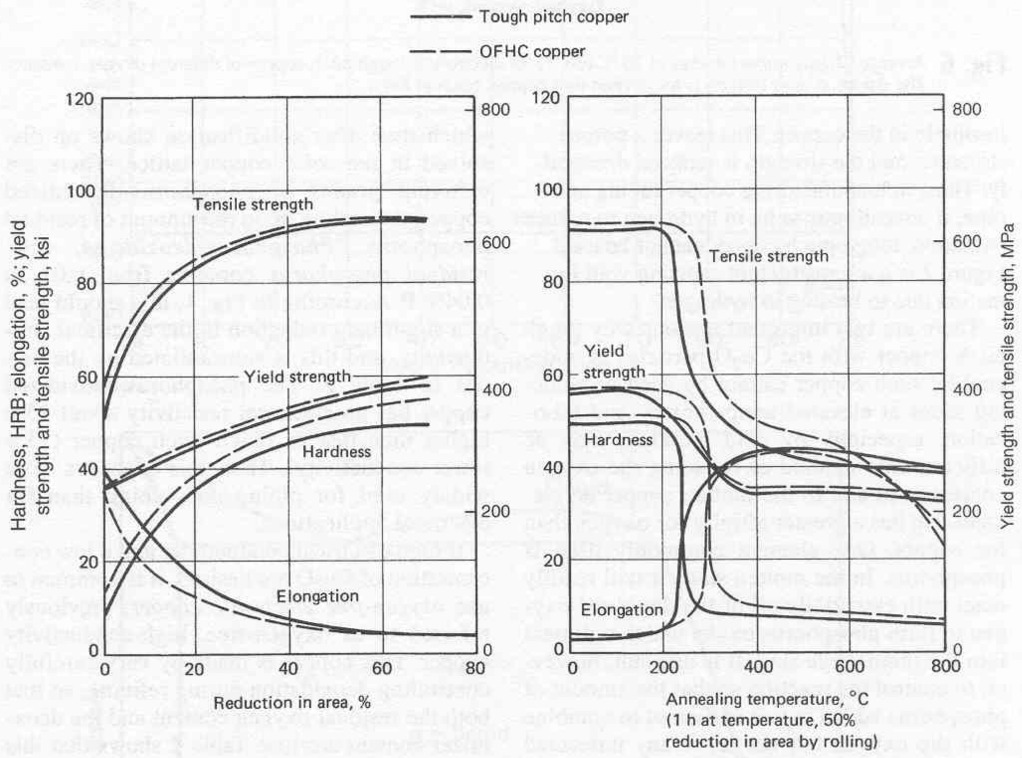
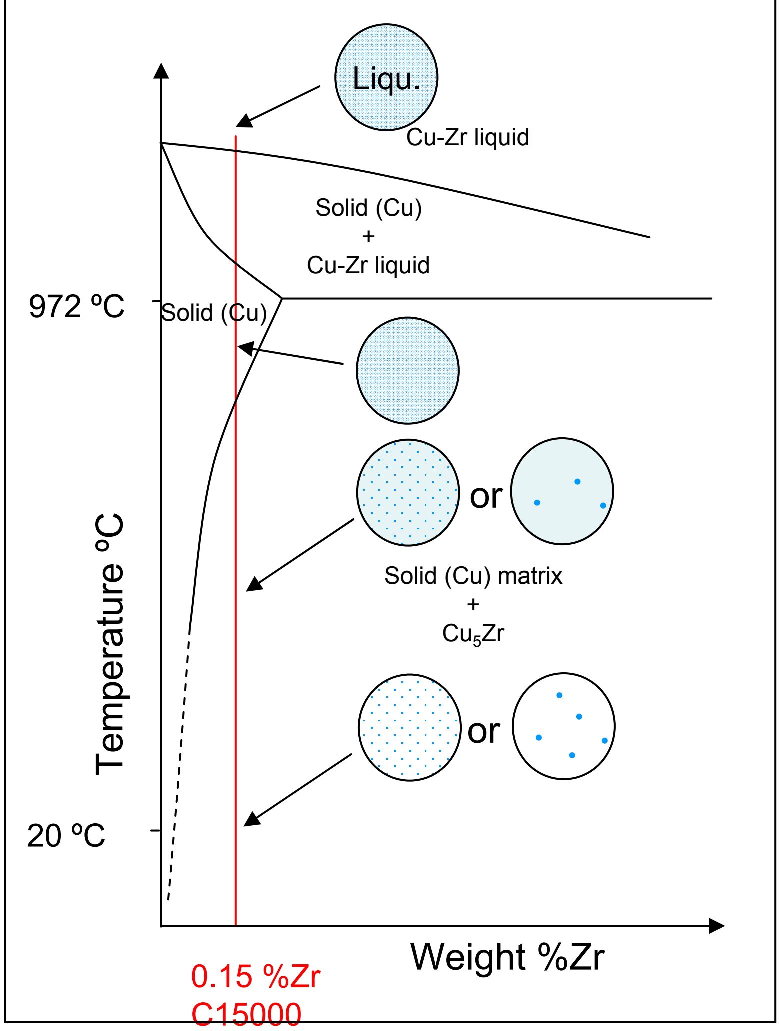


**Fig. 5** Comparison of the effect of cold working (by rolling at 25 °C, or 75 °F) and subsequent annealing on the tensile mechanical properties and hardness of tough pitch copper (0.05% O) and oxygen-free, high-conductivity (OFHC) copper. Note that the two materials are affected in essentially the same way. Source: Ref 3

# Precipitation hardening (applied to CuZr)

**Cu-Zr equilibrium diagram**



**Precipitation hardening** or **age hardening** of CuZr.

- Is based in a series of thermal cycles aiming to favorable change the solid solubility of the phase $Cu_5Zr$

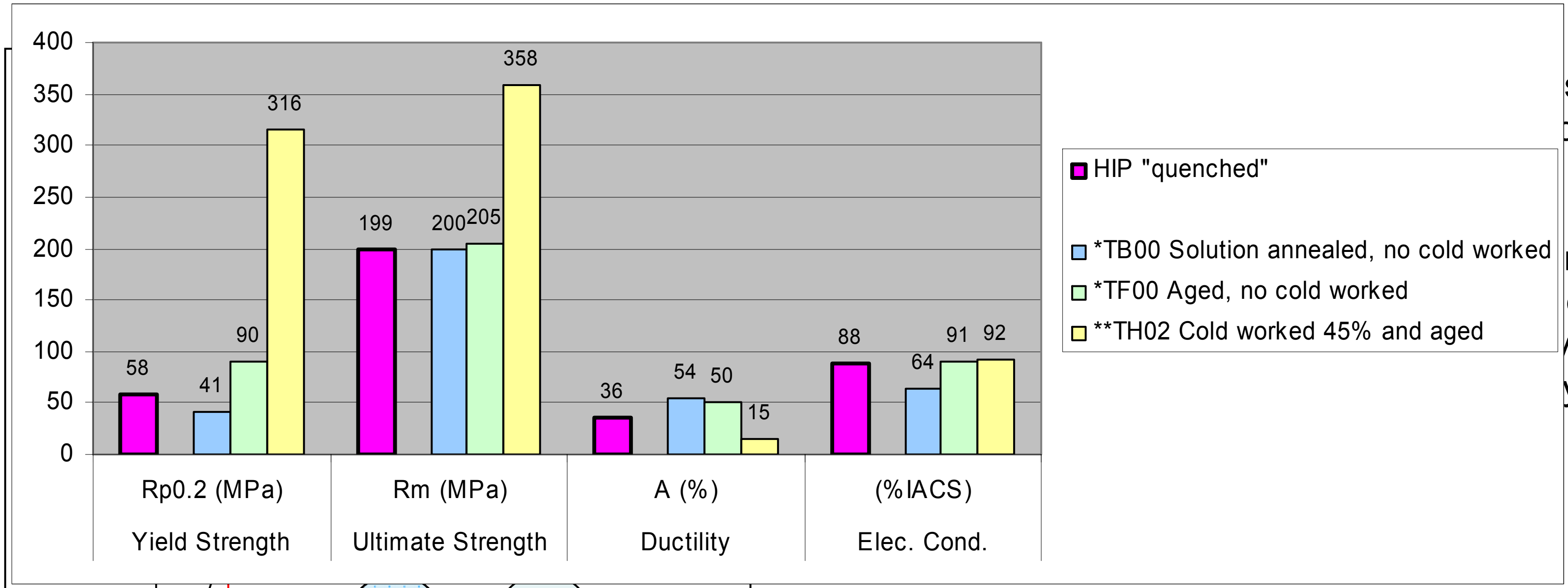
- The Zr atoms of the alloy may be
  - dissolved in the copper matrix
  - or forming $Cu_5Zr$ precipitates.

✓Fine (nanometric) $Cu_5Zr$ precipitates throughout the alloy microstructure provide optimum hardening effect

~Coarse and seldom precipitates are less favorable

✗Dissolved Zr is not hardening but reducing electrical conductivity

# Precipitation hardening (applied to CuZr)



strength

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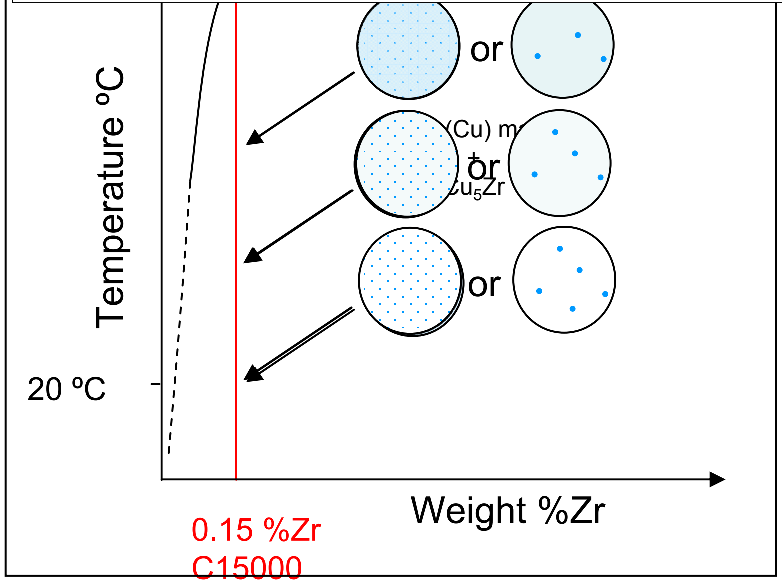
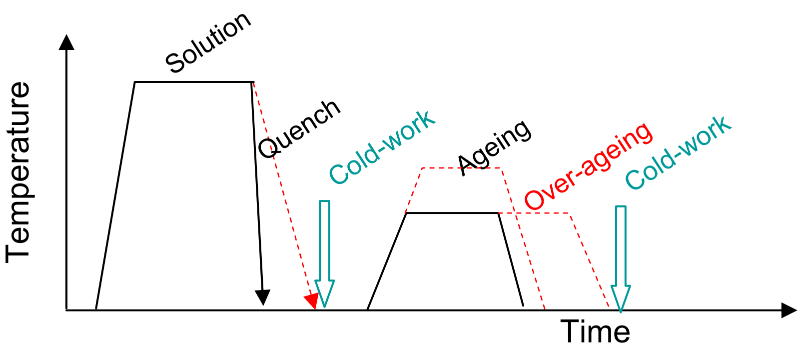


- ✗ Do not over-age: by doing to hot or two long such that precipitates become coarse
- ✗ Avoid a too slow cooling
- ✓ To boost hardening cold-work can be added before and/or after ageing



# Dispersion Hardening (applied to GlidCop)

- Copper base dispersion strengthened

  *Oxide Dispersion Strengthene*
  *GlidCop® Dispersion Strengtl*

- GlidCop, trademark of SCM Metal powders  and pastes for powder me

- Oxides immiscible in liquid Cu ⇒ F consolidation

  *Internal oxidation*
  *Mechanical mixing (Zwilski*
  *Coprecipitation from salt s*
  *Selective internal oxidatior*

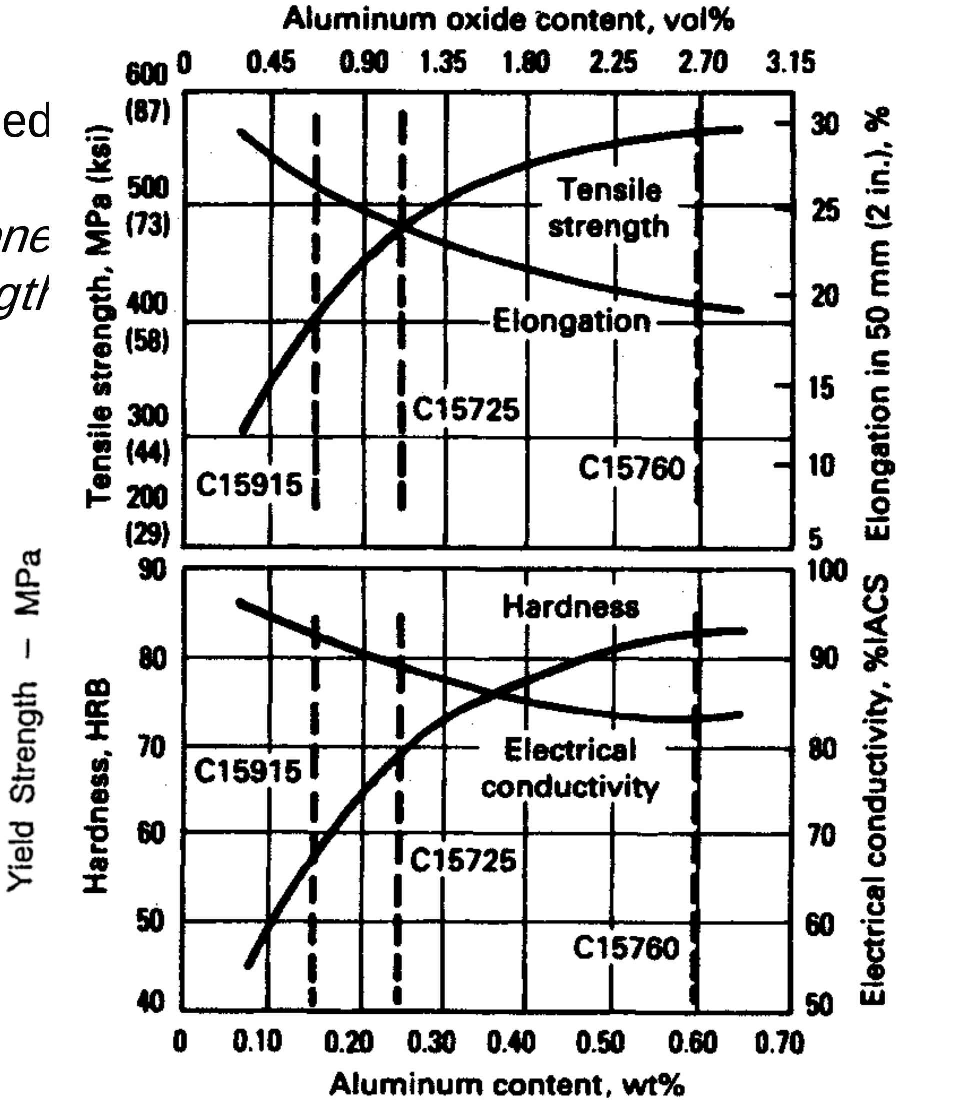
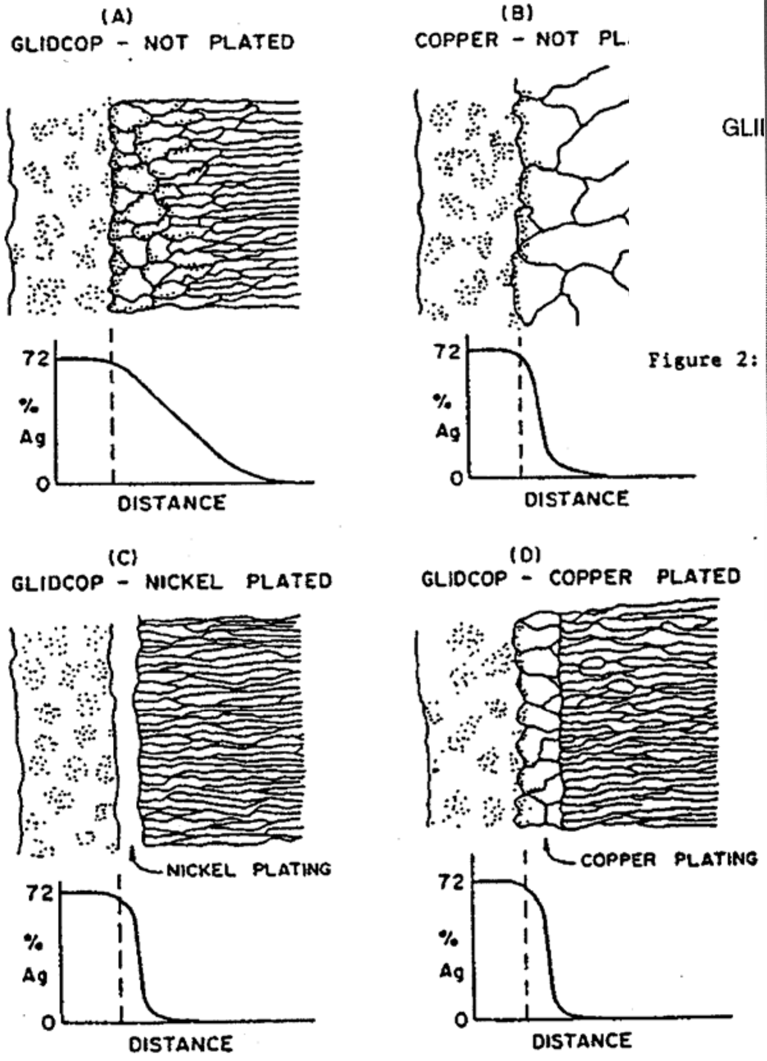
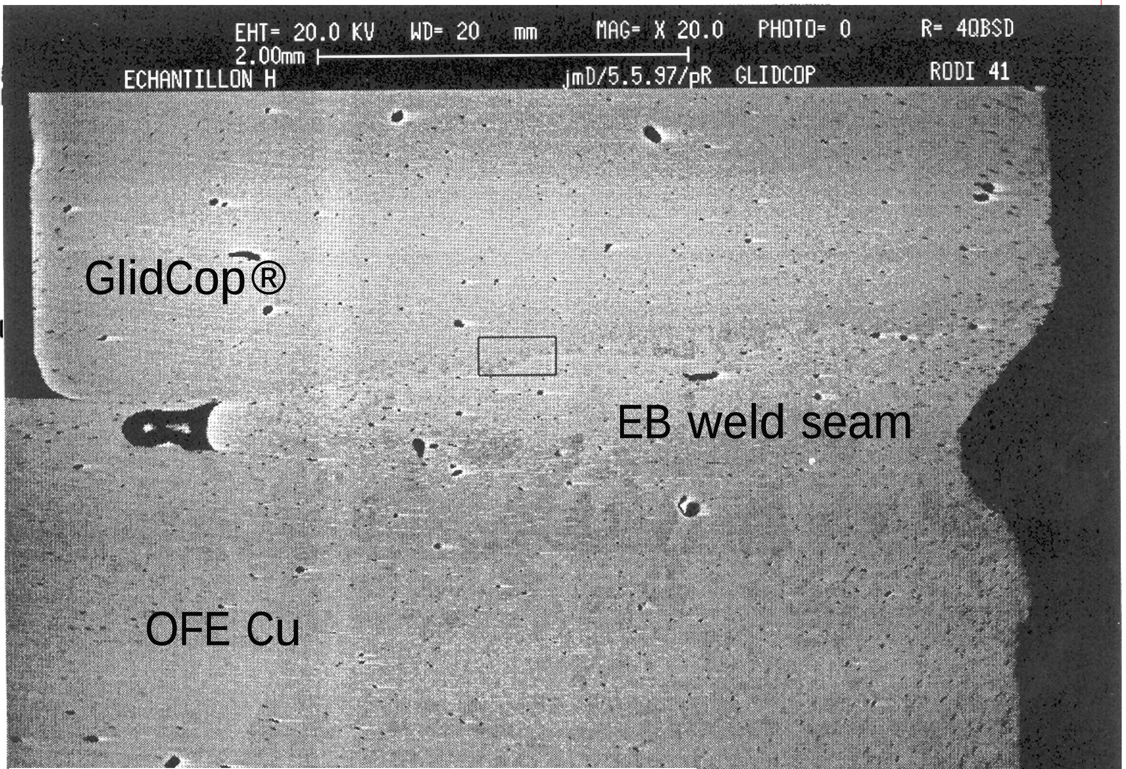


Figure 1: Softening resistance of GlidCop AL-15 versus OF copper and Zirconium Copper. (Note: Properties measured at room temperature, after exposure to elevated temperatures for one hour.)

North American Höganäs tech. data sheet no. 700A (rev. 2003)

# Joining possibilities of GlidCop





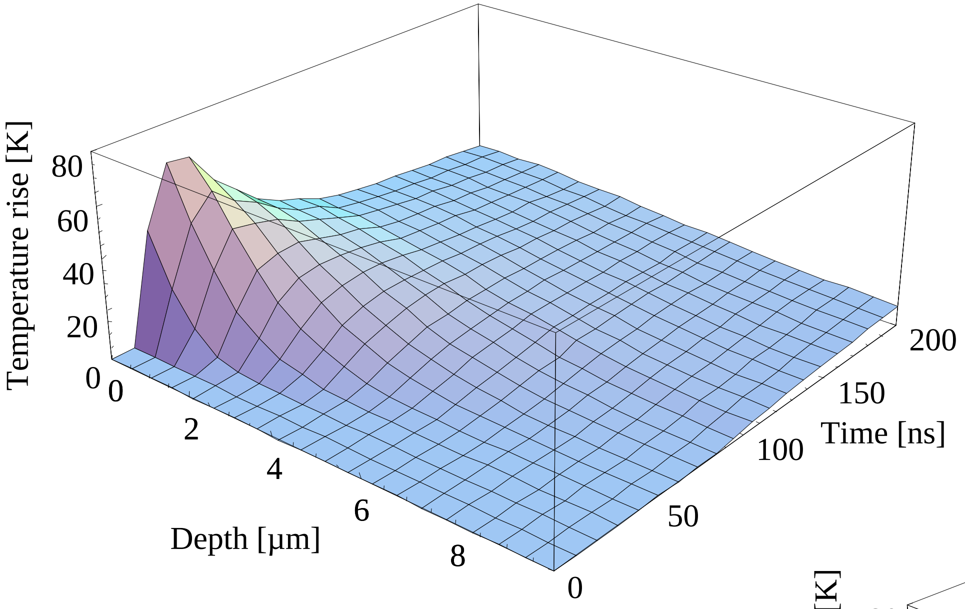
CERN EST-SM-MB report n° 97/04/20

- EB weldable (experience at CERN)
- Welding not suggested by conventional techniques (segregation of the Al oxide)
- Possibly explosion and diffusion bonding

# Fatigue studies

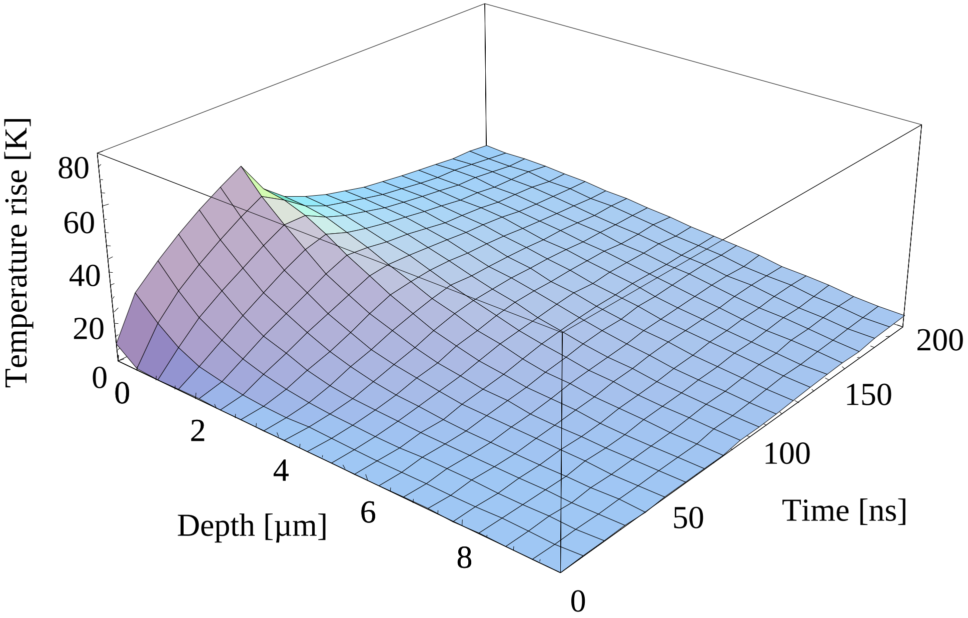
Ongoing R&D.
laser pulses (S. Calatroni, H. Neupert) and
ultrasonic (S. Heikkinen) fatigue tests.

# Low cycle fatigue: UV excimer laser (308 nm) pulsed heating



← Laser pulse

RF pulse ↓

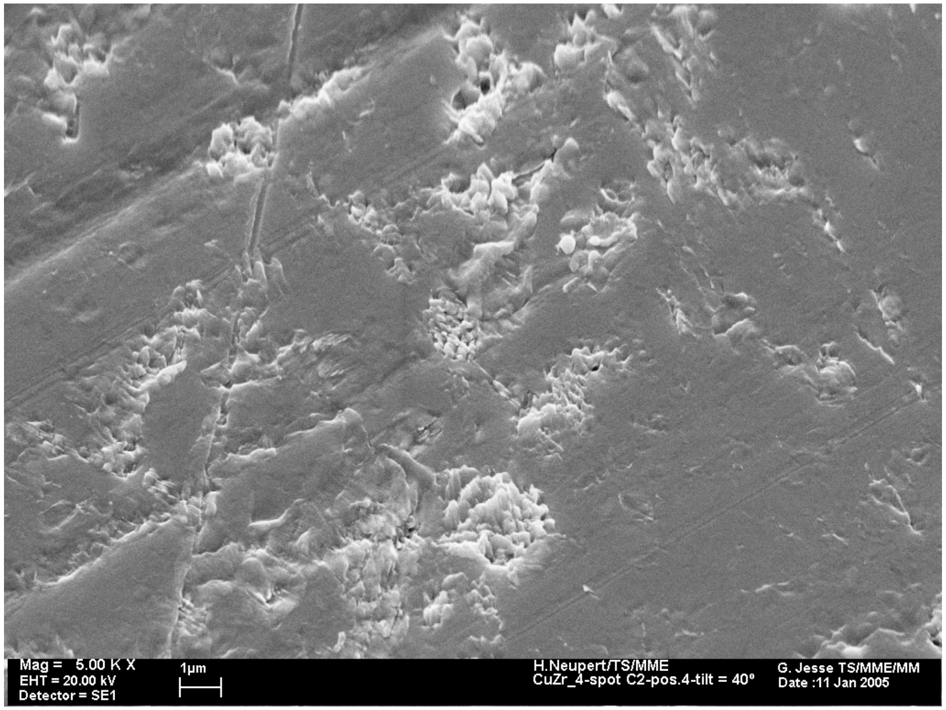


The pulse shapes correspond.
In particular the temperature profile at the peak is very similar, and results in similar stress level.

$$\sigma = \frac{\Delta T * E * \lambda}{(1-\nu)}$$

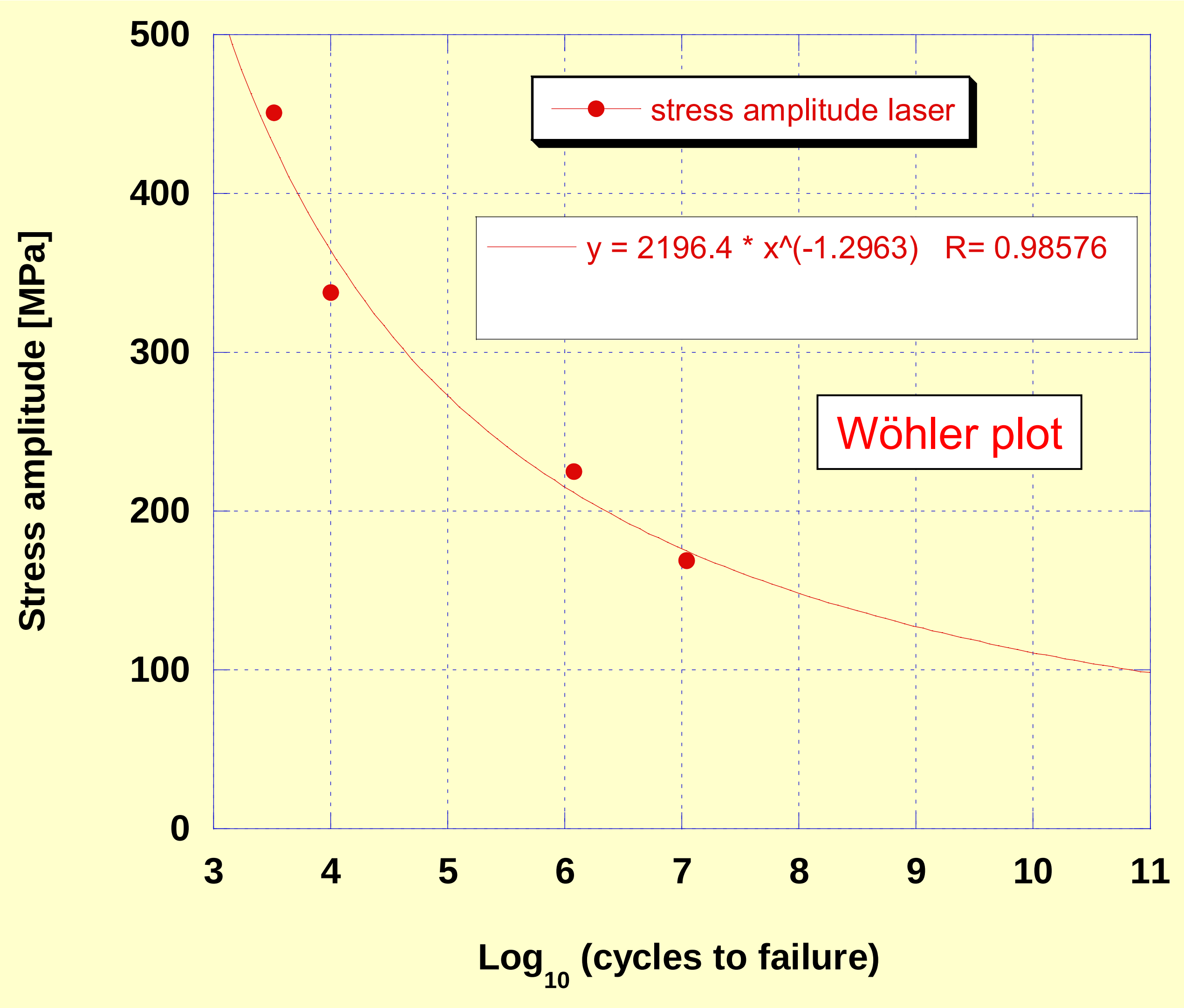
# Laser fatigue: surface modification (→ roughness change)

CuZr C15000 reference surface



CuZr C15000, 10 Mshots, 0.15 J/cm$^2$,
$\Delta T$ = 120 K, $\sigma$ = 170 MPa

# Surface roughness as a function of fluence and number of shots: CuZr



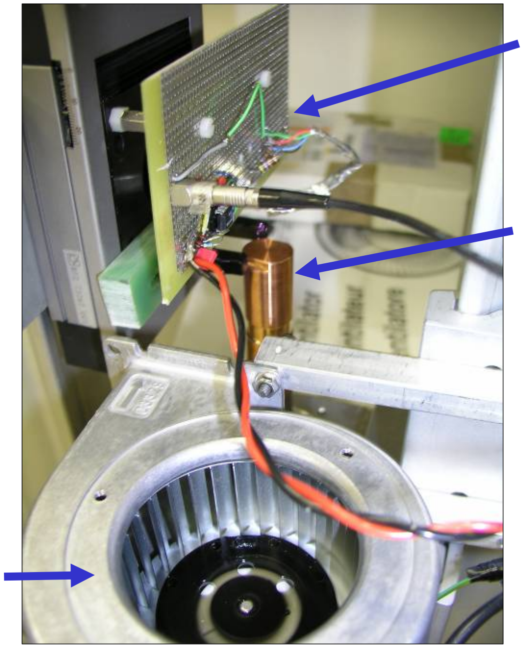
The value of Ra=0.02 µm has been chosen as the first measurable departure from the reference surface (flat, diamond turned).

This is thought to be the most important phenomenon. The further increase of roughness is only crack propagation.

# High cycle fatigue data: ultrasonic testing

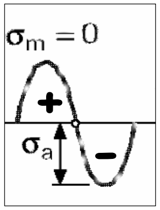
- **Cyclic mechanical stressing of material at frequency of 24 kHz.**
- **High cycle fatigue data within a reasonable testing time. CLIC lifetime 7x$10^{10}$ cycles in 30 days.**
- **Will be used to extend the laser fatigue data up to high cycle region.**
- **Tests for Cu-OFE, CuZr, CuCr1Zr & GlidCop Al-15 under way.**


Ultrasound fatigue test samples

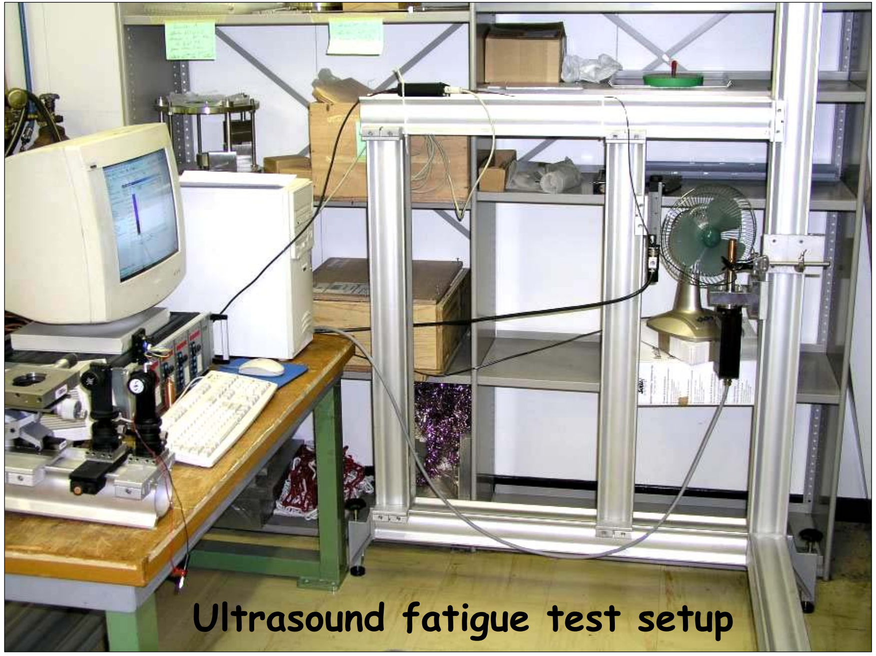

**Calibration card measures the displacement amplitude of the specimen's tip**

**Fatigue test specimen**

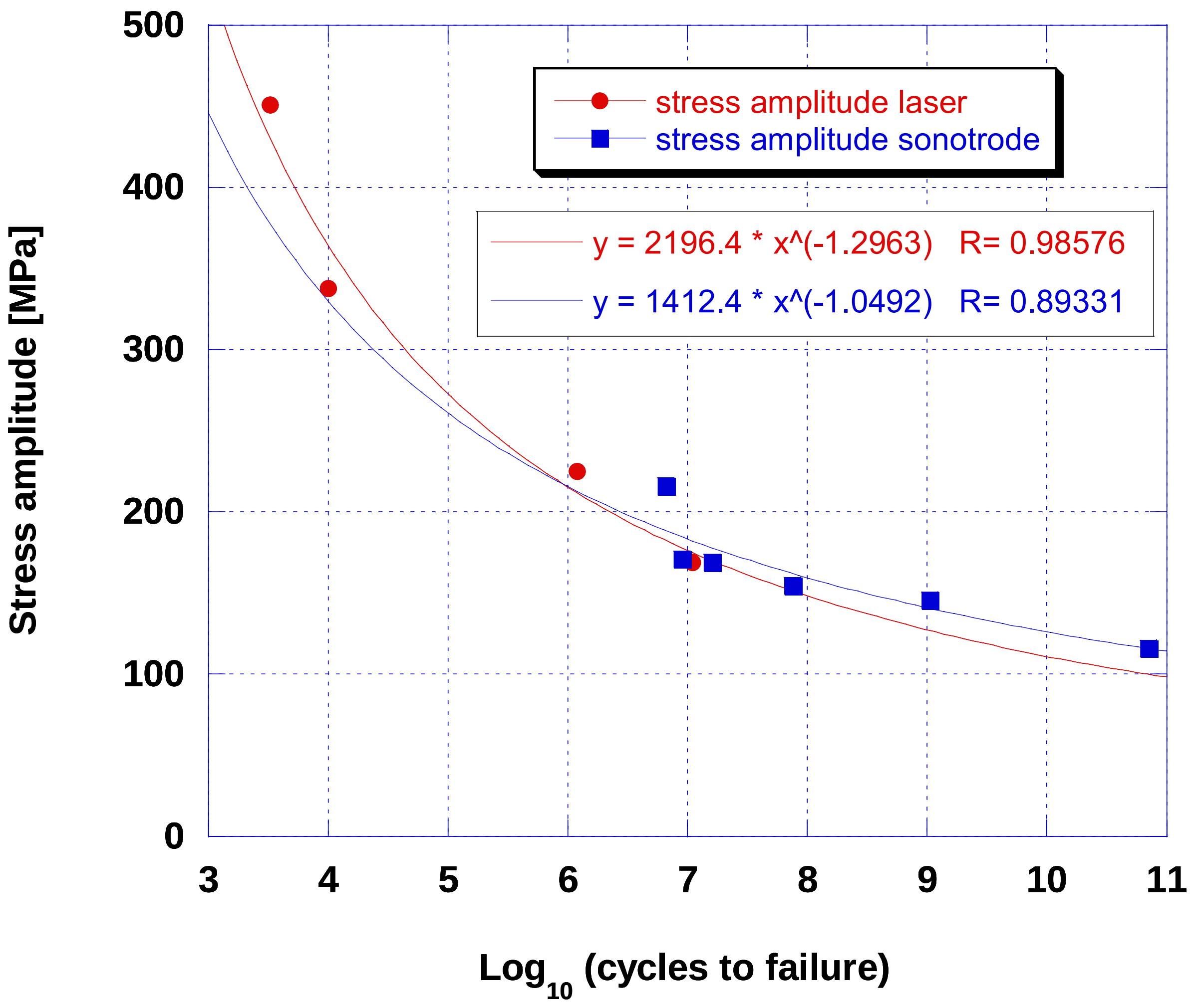
**Air Cooling**



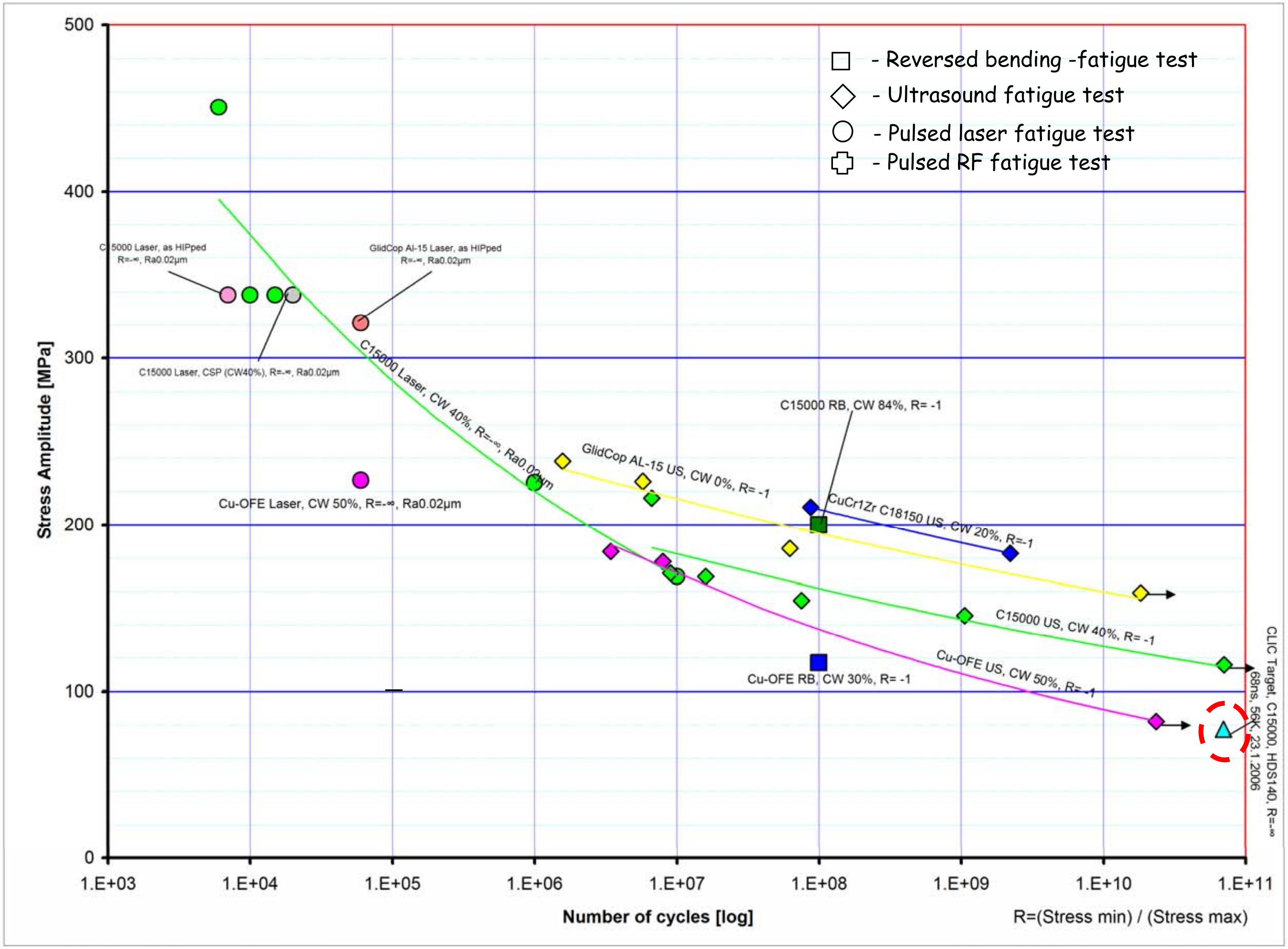
**Reversed stress condition**


Ultrasound fatigue test setup

# Fatigue limit: laser & ultrasound data for CuZr C15000 40% cold worked



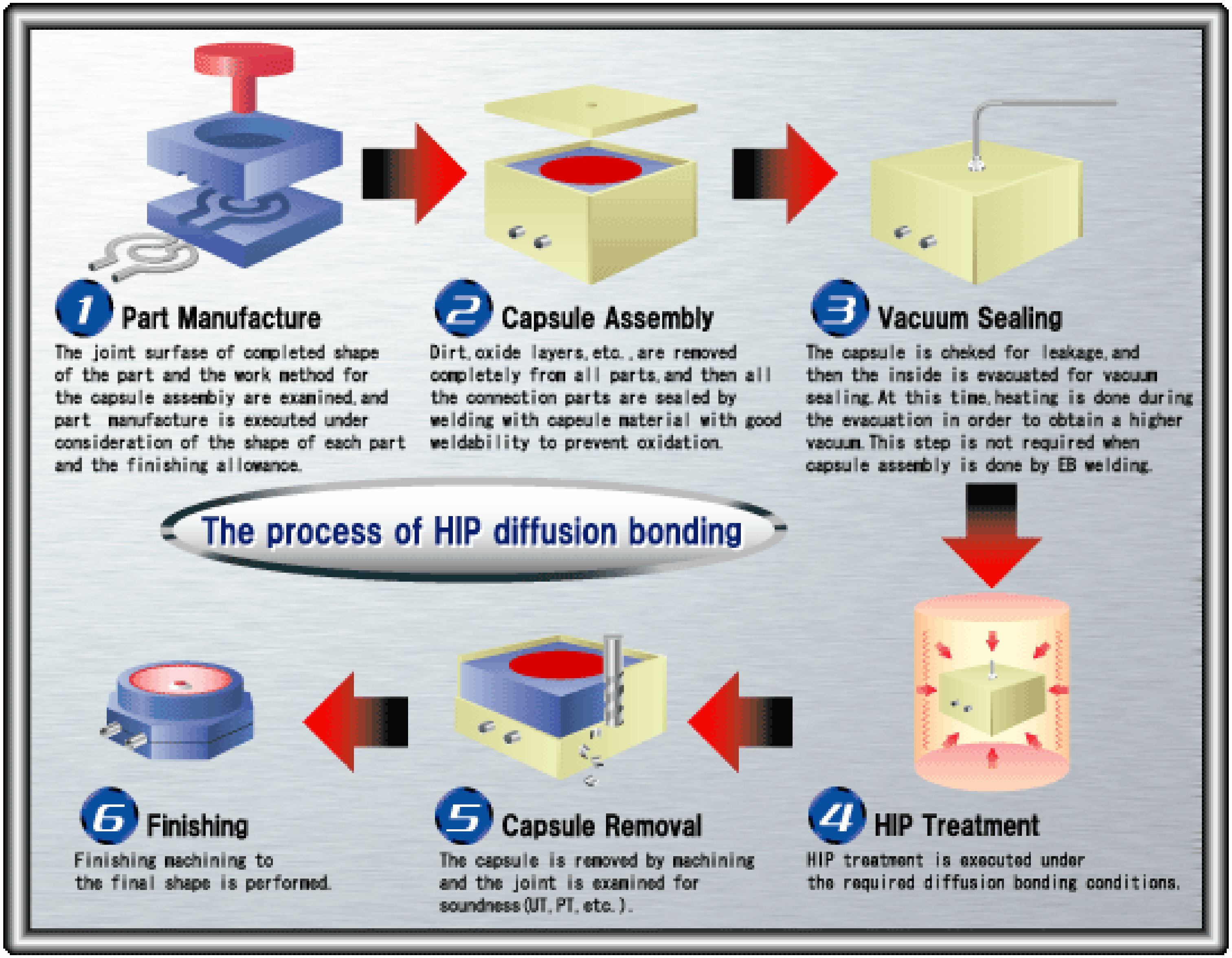
# Laser & Ultrasound fatigue data combined



# Production of bimetallic raw materials

- HIP diffusion bonding
- Explosion bonding
- Other techniques

# Bimetals by HIP diffusion bonding



**1 Part Manufacture**

The joint surfase of completed shape of the part and the work method for the capsule assembiy are examined, and part manufacture is executed under consideration of the shape of each part and the finishing allowance.

**2 Capsule Assembly**

Dirt, oxide layers, etc., are removed completely from all parts, and then all the connection parts are sealed by welding with capeule material with good weldability to prevent oxidation.

**3 Vacuum Sealing**

The capsule is cheked for leakage, and then the inside is evacuated for vacuum sealing. At this time, heating is done during the evacuation in order to obtain a higher vacuum. This step is not required when capsule assembly is done by EB welding.

**The process of HIP diffusion bonding**

**4 HIP Treatment**

HIP treatment is executed under the required diffusion bonding conditions.

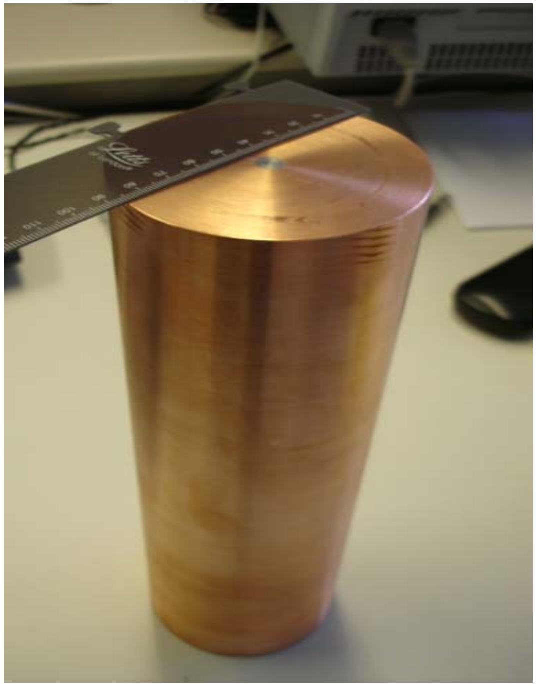
**5 Capsule Removal**

The capsule is removed by machining and the joint is examined for soundness (UT, PT, etc.).

**6 Finishing**

Finishing machining to the final shape is performed.

# Bimetals by HIP diffusion bonding



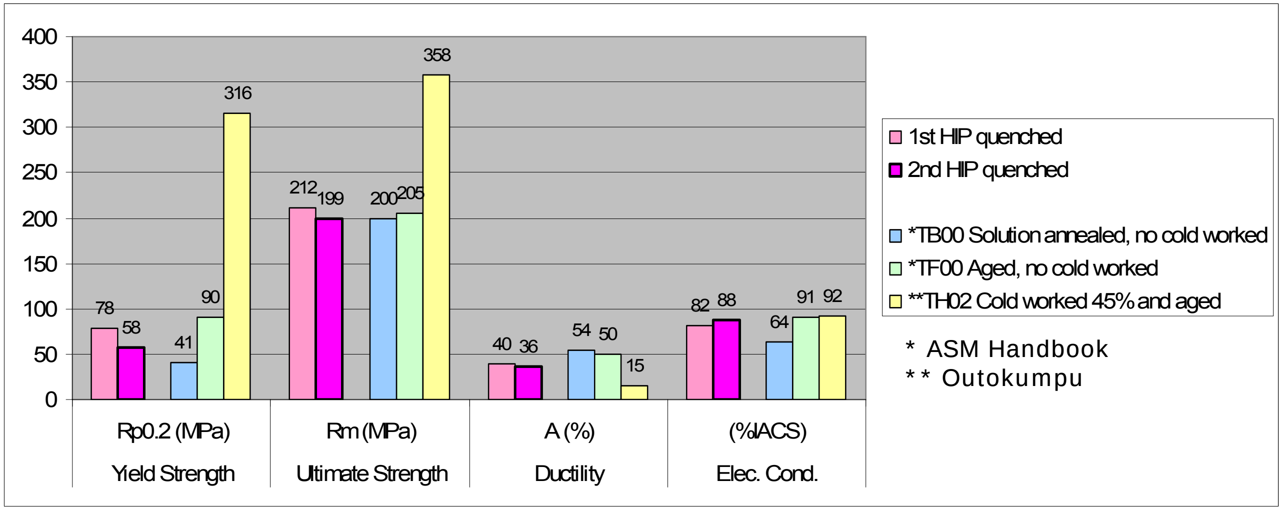
- HIP-diffusion bonding (Metso)
  - Cylindrical configuration, Mo insert, CuZr matrix
  - Attempt to have the CuZr in a solution treated state right after the HIP cycle
    - HIP temperature set up to coincide with solution treatment temperature of CuZr 900ºC
    - Cooling after HIP as fast as possible to try an effective retention of the solution state
  - Test pieces produced for characterization
  - One piece produced for machining of a first bimetallic HDS prototype

- Three concerns:
  - Soundness of the bond
  - Avoid recrystallization of the Mo insert
  - Attainable strength on the CuZr matrix

# Bimetals by HIP diffusion bonding

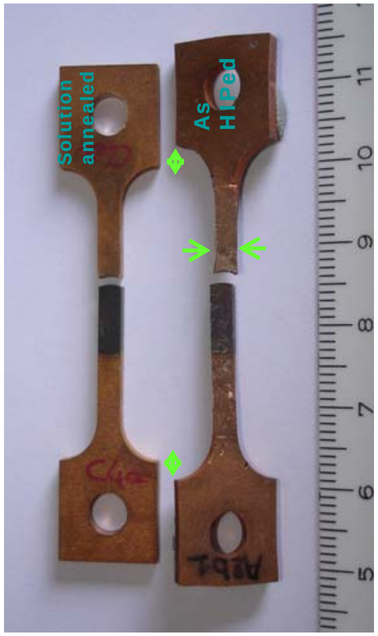
RESULTS

- Bond soundness
  - Good strength and absence of interface voids are proven attainable after HIP cycle
  - Subsequent solution heat treatment + quench weaken the bond.
- Mo insert
  - no recrystallized
- Strength of the CuZr matrix
  - CuZr promising properties and fatigue measurements seen so far are based on an optimum temper state: cold worked and aged
  - Due to the thermal cycles during HIP diffusion bonding the mechanical strength (hence fatigue resistance) of the matrix is not optimum
  - Drawbacks
    - Ageing: proper ageing impaired by a too slow cooling at the end of the HIP cycle
    - Cold work: not feasible in principlePerspectives



* ASM Handbook

** Outokumpu



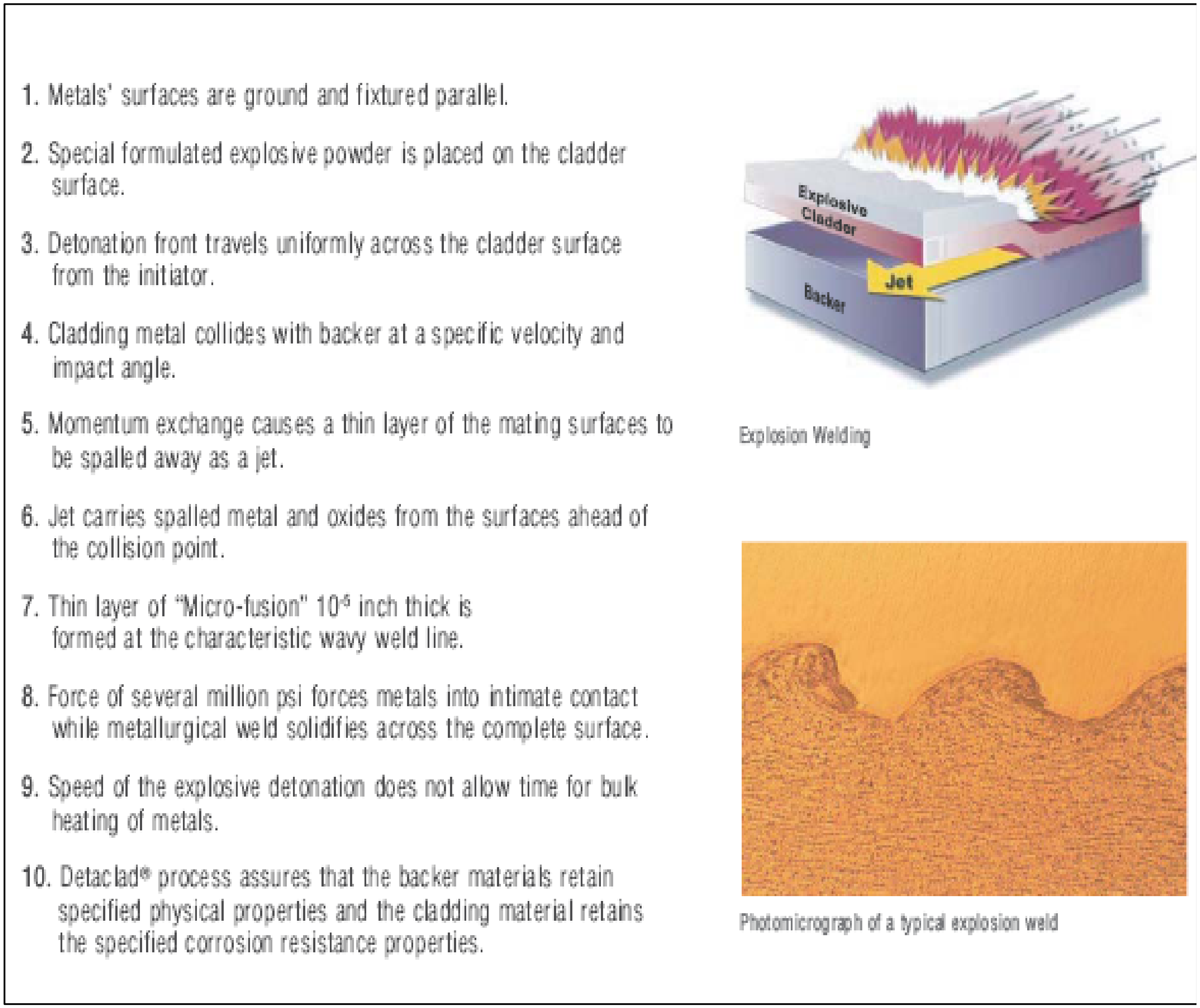
# Bimetals by HIP diffusion bonding

PERSPECTIVES

- Machine the first bimetallic HDS prototype is underway using a HIP-DB rod
- Study alternatives to improve homogeneity of the bond
- Optimize strength and electrical conductivity of CuZr amtrix after HIP by a direct treatment
- Study possible post-treatment to ad cold-work to the matrix: CIP, explosion
- Applicable to GlidCop
- Applicable to Cu-OFE but probably the final state would be completely softened

# Bimetals by explosion bonding

“**Solid state** welding process that is used for the metallurgical joining of dissimilar metals. The process uses the forces of controlled detonations to accelerate one metal plate into another creating an atomic bond… is considered a **cold-welding** process which allows metals to be joined **without losing their pre-bonded properties**.”



1. Metals' surfaces are ground and fixtured parallel.
2. Special formulated explosive powder is placed on the cladder surface.
3. Detonation front travels uniformly across the cladder surface from the initiator.
4. Cladding metal collides with backer at a specific velocity and impact angle.
5. Momentum exchange causes a thin layer of the mating surfaces to be spalled away as a jet.
6. Jet carries spalled metal and oxides from the surfaces ahead of the collision point.
7. Thin layer of “Micro-fusion” $10^{-5}$ inch thick is formed at the characteristic wavy weld line.
8. Force of several million psi forces metals into intimate contact while metallurgical weld solidifies across the complete surface.
9. Speed of the explosive detonation does not allow time for bulk heating of metals.
10. Detaclad® process assures that the backer materials retain specified physical properties and the cladding material retains the specified corrosion resistance properties.

Explosion Welding

Photomicrograph of a typical explosion weld

# Bimetals by explosion bonding

- Explosion bonding (R. Stefanovitch)
  - Flat configuration, using CuZr back plate already in an optimum cold-worked and aged state
  - Bonding process does not affect the starting properties of Mo and CuZr
  - Test pieces produced for characterization
  - Pieces for machining of bimetallic HDS prototype are underway
- Two concerns
  - Soundness of the bond
  - Avoid damaging of the starting materials

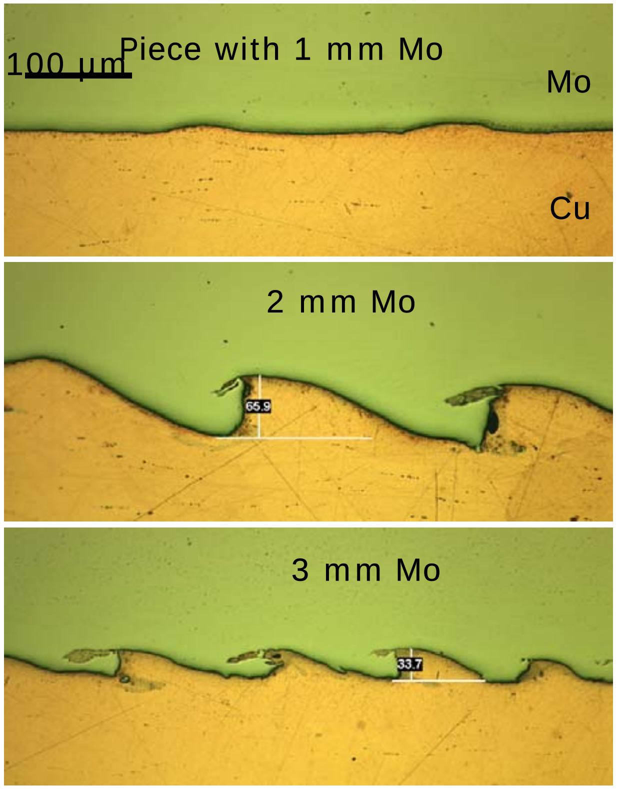
# Bimetals by explosion bonding

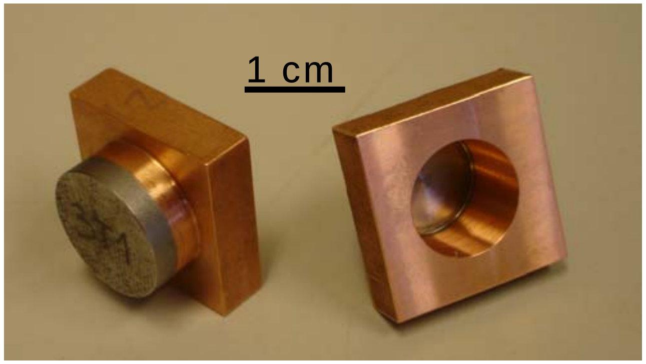
RESULTS

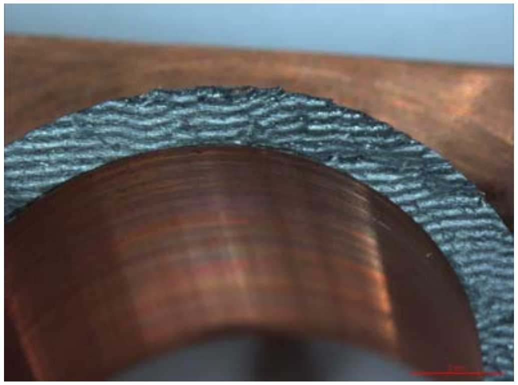
- Bond soundness
  - Good strength and absence of interface voids
- Possible fragilisation of the Mo in a layer close to the interface

PERSPECTIVES

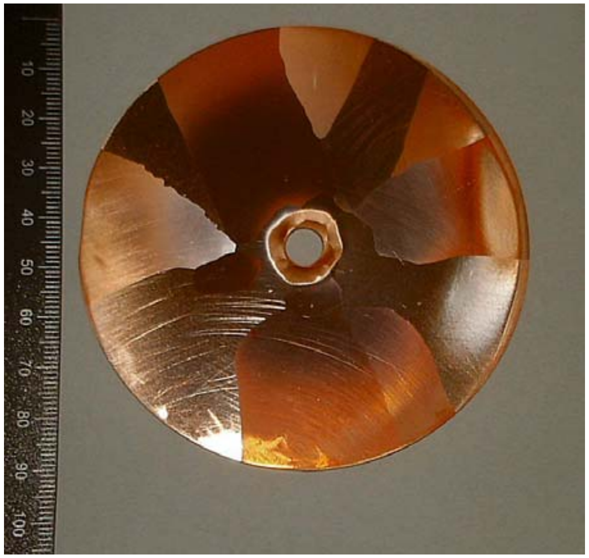
- Production of pieces for machining HDS prototype is underway
- Study possible curved configuration to better adapt to the geometry of the HDS structure







# Other techniques



▲Coextrusion with intermediate layer (Lutch).

◄Vacuum casting over a solid insert (Starck).

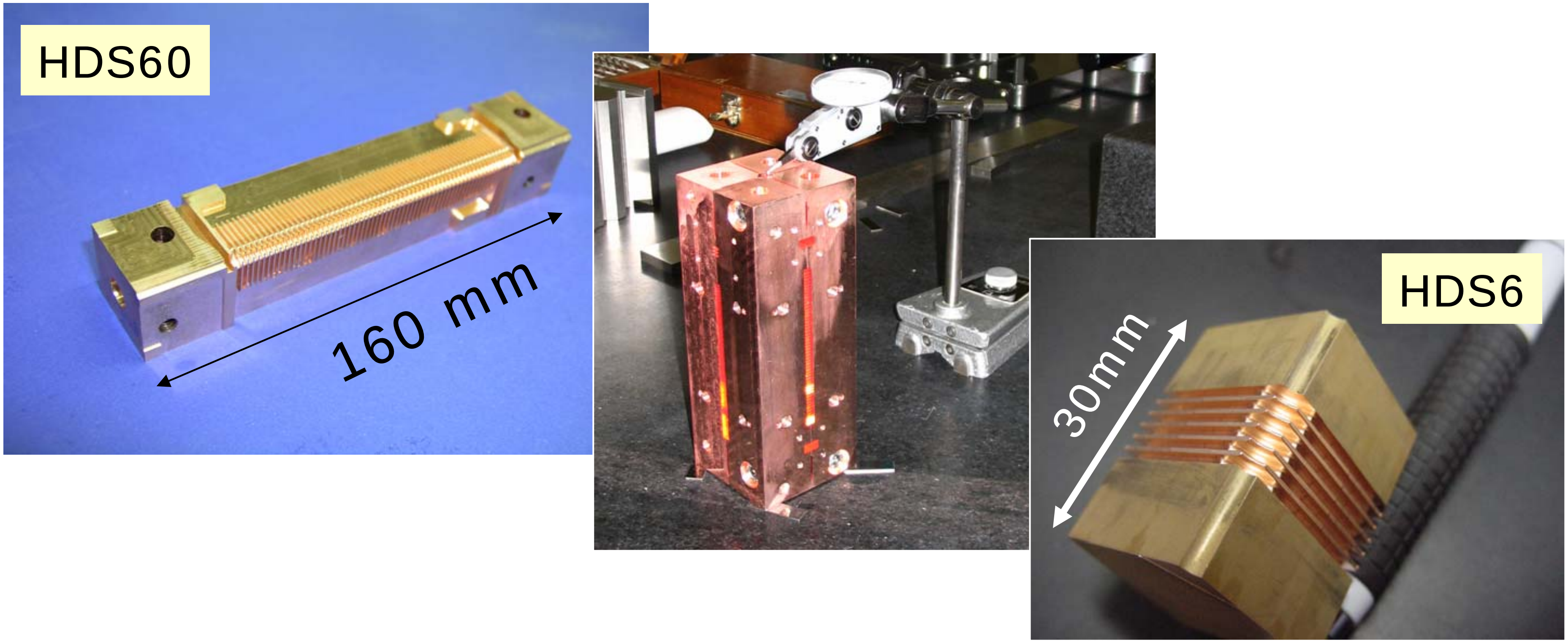
# Machining to tight tolerances

- Milling
- Evolution of accuracy
- EDM

# Existing HDS (in Cu-OFE): produced by milling

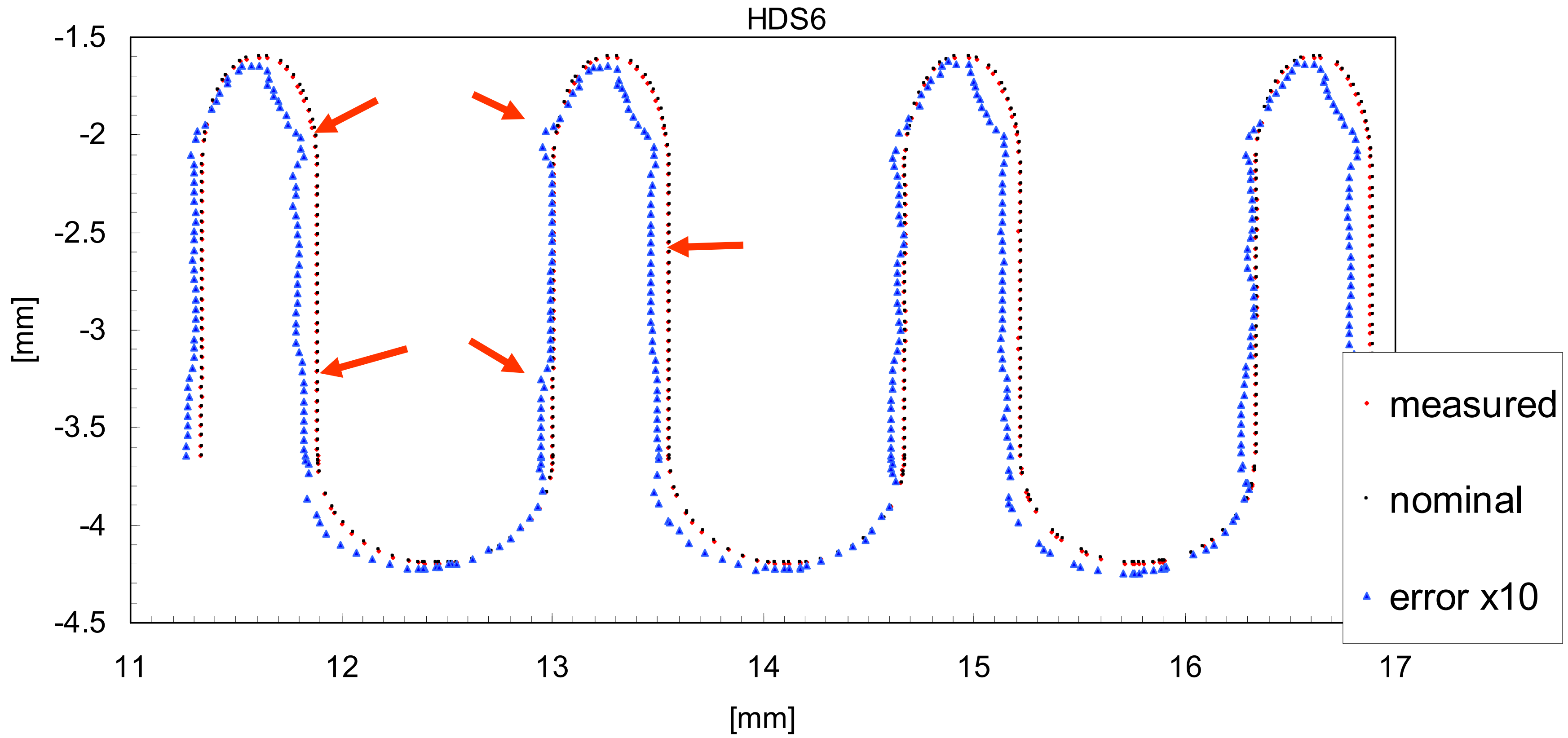
→ HDS60: +/- 15µm accuracy, assembly at +/- 10µm, low power RF test successful: next week in high power test facility CTF3

→ HDS6: precision +/- 10µm



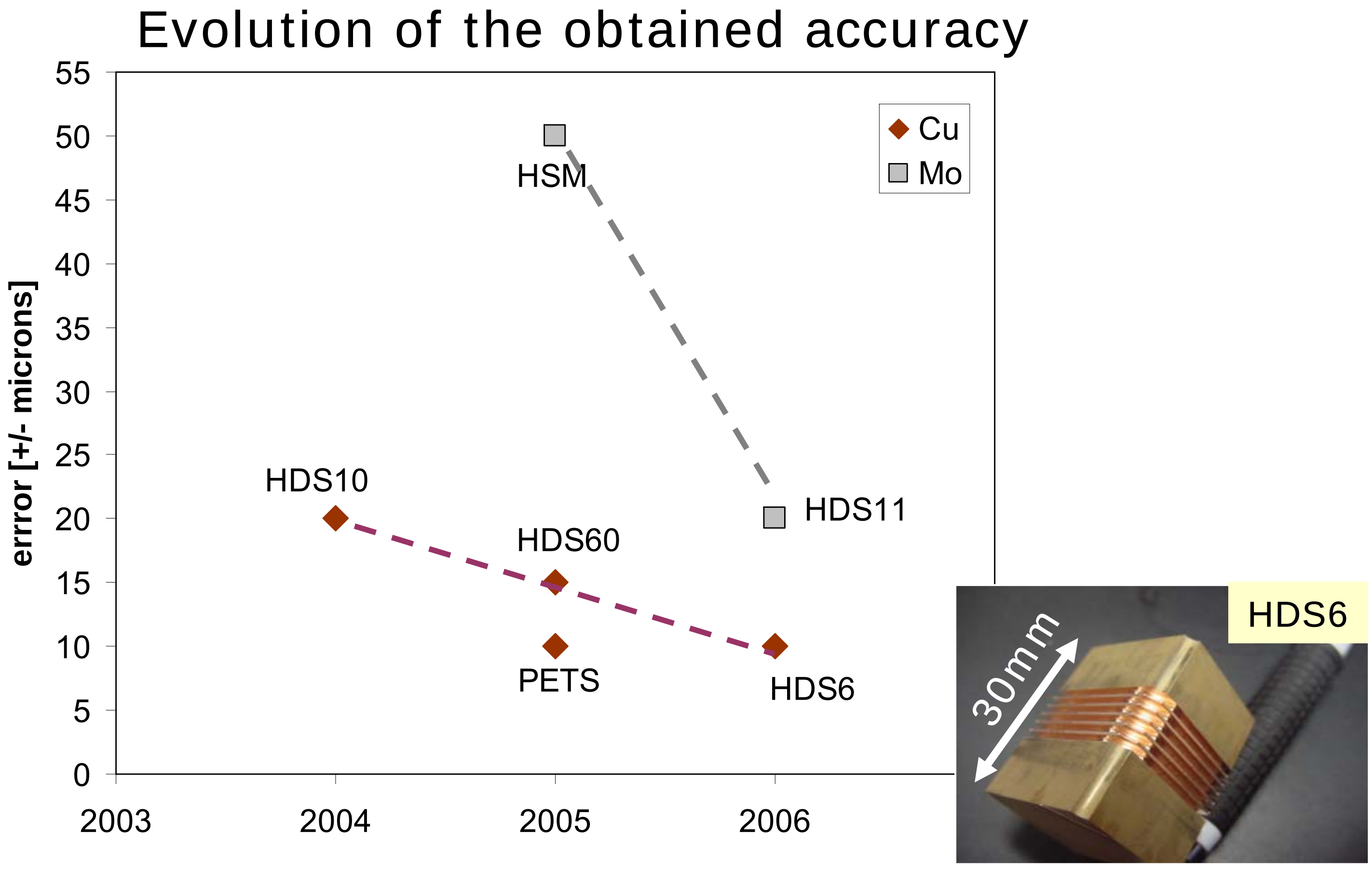
# Contact profile of HDS6

Measurement: 0.1N force, accuracy +/-3 µm (in house), scan pt. by pt. on the surface



# Evolution of the machining accuracy

Parts made by various firms, all in milling

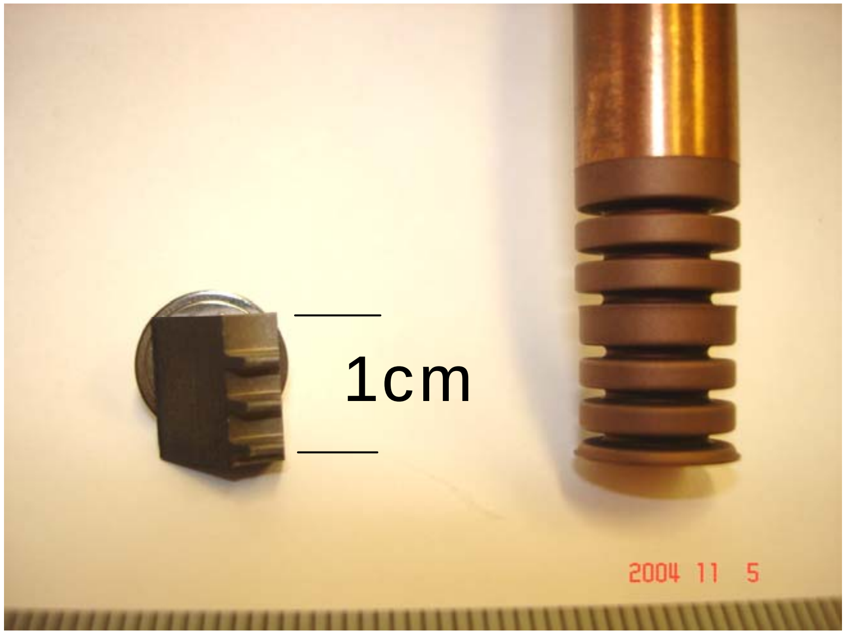


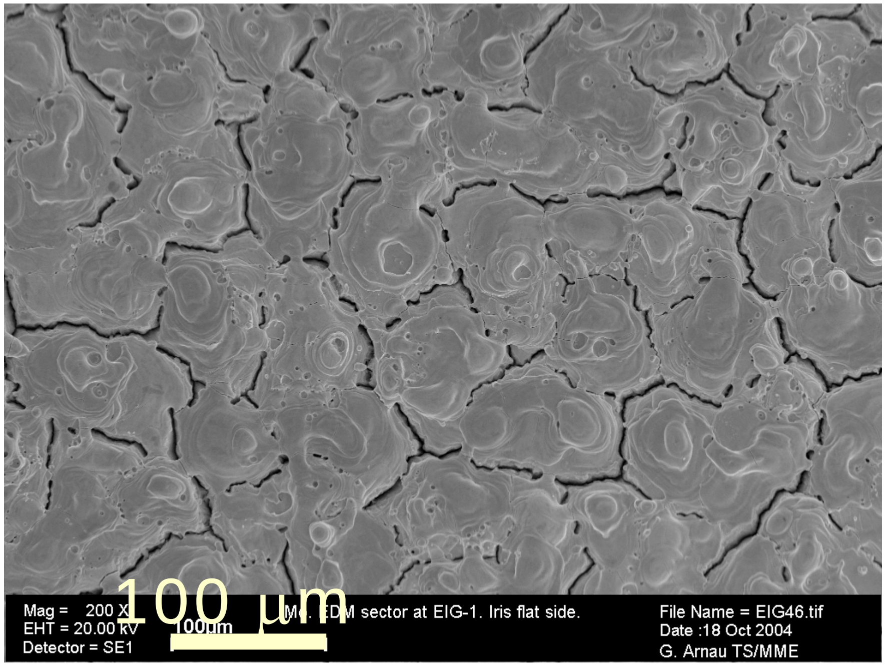
Evolution of the obtained accuracy

# EDM machining with rotating electrode

**EDM on Mo (**Ecole d'Ingénieurs Genève)

- problems: micro cracks





# Conclusions

- -A combination of materials may cope with the stringent requirements of high gradient structures
- -First prototypes of HDS bimetallic and to limited tolerances are on the way. They will be functional prototypes to be tested at CTF3
- -R&D on materials consolidates and carries on:
  - -DC and RF breakdown tests….
  - -Proven validity of strategy to test up to very high cycles thermal induced fatigue.  Now increasing statistics for accurate life prediction and broadening range of materials tested.
  - -Proposals for improvement of CuZr-Mo bimetallic performance and geometry, broader possibilities if other materials like GlidCop

# Acknowledgements

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